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PROGRESS ON PROBABILISTIC ASSESSMENTS OF REACTOR CORES FOR PRESSURE TUBE CRACKING DUE TO HYDRIDE BLISTER FORMATION

Report No. 88-325-K

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This report describes progress in the development of a computer model designed to provide a probabilistic assessment of pressure tube cracking due to blister formation at pressure tube - calandria tube contacts. The model has been significantly modified over the past year and a half in order to complete a rapid assessment of Pickering Unit 3 and 4 reactors following the removal of channel P3-L09 and the subsequent sampling of the deuterium levels in 20 channels in P4 and in 10 channels of P3. This report describes the changes in the model.

job	file	date	report no.
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EXECUTIVE SUMMARY

PROGRESS ON PROBABILISTIC ASSESSMENTS OF REACTOR CORES FOR PRESSURE TUBE CRACKING DUE TO HYDRIDE BLISTER FORMATION

D.V. Leemans, T.P. Byrne and M. Leger

This report provides a detailed description of the computer model used for probabilistic assessments of the numbers of tubes in a reactor core with hydride blisters large enough to initiate delayed hydride cracking. This model has been under development since 1985 and has undergone several significant changes since last reported. In particular, the concept of a critical blister is developed and the basis for its use is described.

This computer model has recently been used to assess the state of the Pickering Unit 4 core based upon inspection information.

The assumptions and limitations of the model are outlined. Detailed appendices show how inputs to the model are derived and used. Checks of the performance of key subroutines are described.

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PROGRESS ON PROBABILISTIC ASSESSMENTS OF REACTOR CORES FOR PRESSURE TUBE CRACKING DUE TO HYDRIDE BLISTER FORMATION

1.0 INTRODUCTION

The probabilistic assessment model described in this report has been under development since late 1985. It was recognized then that the application to reactor assessment of the understanding of the blister growth and fracture phenomena being generated by the TRAC (Tube Response After Contact) program would be very difficult on a deterministic basis given the inherent variability of both pressure tubes and operating factors in the reactor. In order to accommodate this variability while assessing a complete reactor core, a model was developed based on Monte Carlo techniques to calculate the probability per tube of having both contact and hydrogen equivalent exceeding a threshold value. Descriptions of this model at earlier stages of its development as well as its application to reactor assessments for both SLAR and REFAB have been reported previously/1,2/.

During the past year, the emphasis on the model development was placed on making a good representation of blister growth which was not present in previous versions. This work involved using the blister growth finite difference model developed under the TRAC program to generate blister growth information for use in the probabilistic modelling. A report describing the use and modification of the finite difference axisymmetric model used to carry out this work is in preparation. In addition to the blister growth modelling work, major modifications to the probabilistic model were also implemented in order to be able to accommodate blister growth inputs. There were fairly fundamental changes both in the way in which the contact location was determined and in the degree of flexibility allowed in the choice of input parameters.

The computer programs developed are called RABIT (Reactor Assessment for Blisters In Tubes) with suffixes to identify the particular version. The differences between versions are described in this report.

This report includes a description of the treatment of the inputs, a model description, recommendations for future development and appendices containing detailed descriptions and validation of key parts of the model.

2.0 MODEL OUTLINE

The model has been developed in several stages. While the basic model remains schematically the same, increased sophistication in dealing with contact spreading, deuterium pickup rate and the uncertainties in the different variables is now in place. As mentioned elsewhere, blister formation and critical blister formation in a pressure tube require that two conditions be fulfilled.

1. The pressure tube contacts the calandria tube.

2. The equivalent hydrogen content in the bulk of the tube near the contact point exceeds a threshold value.

The basis for the concept of a critical blister is discussed in some detail in Appendix 1. Blister growth modelling used to determine thresholds for critical blisters is described in Appendix 2.

The main refinements in the model compared with earlier versions/1,2/ are:

1. Deuterium pickup rate and blister thresholds are a function of the PHT temperature local to the contact.

2. The contact is allowed to spread axially as a function of time.

3. Differences between channels with east and west inlets (referred to as East and West tubes) are now explicitly taken into account. This was a necessary development due to the observation that garterspring position distributions for channels with east and west inlets are significantly different.

4. In order to deal effectively with a range of deuterium pickup models two separate programs have been developed: in the first one the deuterium pickup is model based; in the second one the deuterium pickup is data based.

5. Three types of distributions for the random variables are allowed: normal, lognormal and Weibull.

The programs to calculate the probabilities of critical blister formation work according to the following procedure (shown schematically in Figure 1 where the subroutines called to carry out these operations are identified for each version of the program):

1. Selection of a random set of garterspring locations. The details of this procedure are discussed in Appendix 3.

2. Selection of a value of the random variable initial hydrogen. This variable can be sampled from a database or from a distribution.

3. Calculation of contact location using Sakaguchi's nomograms. All the contact work is explained in Appendix 4.

4. Calculation of the time to contact assuming that the channel is in the central core. This random variable has a distribution with a user defined standard deviation.

5. Appropriate scaling of the contact time if the channel is in the intermediate or outer zone.

6. Calculation of exact contact location at time of contact.

7. Calculation of the outer contact points for each year after initial contact. The spreading model is outlined in Appendix 5.

8. Calculation of the temperature at these locations. An additional degree of variability is recognized by allowing variability in the outlet temperature about the mean outlet temperature defined by the temperature profile used. This variability is scaled along the length of the tube.

9. Calculation of the time at these locations for hydrogen to reach the threshold for blister formation. This requires knowledge of the pickup rate as a function of time at these temperatures and locations. Different pickup rate models can be accommodated as outlined in Appendix 6.

10. Calculation of the time to reach the hydrogen threshold for critical blisters at these locations. This threshold is complicated by the fact that it is pickup rate dependent and, therefore, possibly time dependent also.

11. Storage of the shortest time for both blister formation and critical blister formation and investigation of what happens by further spreading. The process (7-10) is repeated as often as necessary.

12. Calculation and storage of the earliest time at which both conditions are met.

13. Repetition of the process. (Back to 1).

These steps complete the Monte Carlo process. The post-processing includes:

1. The data on channels with east and west inlets are collected separately.

2. Calculations of the probabilities of blister formation and critical blister formation. Estimates of the mean and variances of the number of critically blistered tubes are derived. The reliability and its variance are calculated. The necessary theoretical calculations are summarized in Appendix 7.

3. The input data are summarized and the results are plotted.

2.1 COMPUTER PROGRAM VERSIONS

In this section the different existing versions of the computer program RABIT are described. As noted above, two fundamentally different models of deuterium pickup have been accommodated in two separate versions of the program: RABIT_PL has been written to model piecewise linear pickup; RABIT_DB is the corresponding program for the databased pickup model.

Different versions of the subroutines required to establish both the time of contact and the contact location were also necessary because of the differences between Pickering and Bruce reactors in terms of channel creepsag. Therefore, there are actually four different versions of the program. The discussions of the developments of the inputs in the appendices are limited to the Pickering Unit 3 and 4 cases although similar developments for the Bruce Unit 1 and 2 cases have been completed.

(Since these programs were written, development has continued. This has resulted in an updated program which incorporates all four versions into one. Other modifications have also been made, particularly in the area of statistics of the realizations and in the output completeness. These changes will be described in a later report. This report provides an overview of the program with only minor changes from the version used to carry out the assessment of the Pickering 4 reactor following the first microsampling program/3/).

2.2 LIMITATIONS OF THE MODEL

The present computer model, while allowing for a more sophisticated modelling of blister formation and growth than the earlier work, still has a number of limitations.

1. The model deals with only one time-independent thermal boundary condition at the contact area.

2. Contact time and location are based on ABAQUS runs using the CRNL 1993 creep equation; newer creep equations (CRNL 4000) are presently being reviewed for possible use. Furthermore, for the intermediate and outer zones scaling terms are used which should be reviewed.

3. Contact time is a random variable in this model; however, contact location and contact spreading are not.

4. The program considers only blister formation in the first contact area. Secondary contacts are ignored. This simplification in the analysis affects mainly the results after twenty years.

5. Several assumptions underlie our use of the garterspring location distribution:

   * garterspring do not move;
   * the reported measurements are accurate and are representative of the distribution in the reactor.

6. Concentrations for critical blister depths are based on blister growth computer runs for cases in which contact occurs before the bulk tube concentration reaches a level which allows blister growth. For late contact, our predictions are conservative.

3.0 PREPARATION OF THE INPUTS

The model requires detailed inputs on a large number of parameters, including garterspring position, initial hydrogen content, deuterium pickup and threshold values for blister formation and critical blister formation. Furthermore, the temperature profile along the pressure tube and the relationship between contact temperature and PHT temperature have to be included in the inputs. Appendix 8 outlines in detail, the structure and content of the different input files.

4.0 DESCRIPTION OF THE OUTPUT

The output is largely self-explanatory. An example of the output is shown in Appendix 9. First, it provides a comprehensive summary of the inputs used for the particular run. Then, some statistics of the inputs used for the actual Monte Carlo realizations are summarized. The purpose of these statistics is to provide a rapid method of checking the operation of some parts of the program. The first four statistics are collected for all the realizations, whereas the final four relate solely to those realizations in which blisters were obtained. Finally, line printer plots of the time dependence of the probabilities, numbers of tubes with blisters and the reliability are provided.

5.0 RECOMMENDATIONS FOR FUTURE WORK

The many limitations mentioned above indicate areas where improvements can be made in the model. Another guide to future development would be the results of detailed sensitivity studies which would allow improved identification of the inputs which greatly influence the outputs.

Recommendation 1: Carry out a detailed sensitivity analysis to estimate the uncertainties of the outputs due to the lack of precise knowledge of the inputs. (The uncertainties due to the Monte Carlo simulation are routinely calculated in the program).

Recommendation 2: Establish a decision making process re the inputs to the model. Unfortunately, it has been left up to the model developers to make decisions on such inputs as gartersprings (should the data of P3 and P4 be merged?) contact time (should CRNL 1993 or 4000 be used?), deuterium pickup (piecewise linear or power law, influence of iron, influence of temperature) and others.

Recommendation 3: Develop a more systematic method to assess the reliability of the whole reactor. The scaling factors used to assess channels in the intermediate and outer zone are derived from early TUBESAG runs and assume similar sags over large ranges of flux for channels in the intermediate zone. This may not be realistic.

Recommendation 4: Make an immediate decision on the choice of design equation. This is particularly important due to the influence of this choice on contact time. It is anticipated that with CRNL 4000, secondary contacts would become more important and cannot be ignored any longer. The inclusion of secondary contacts in the model would require a substantive rewrite of the model.

Recommendation 5: Establish the evolution of thermal boundary conditions as a function of time. The stationary scenario is a great simplification and may be unnecessarily conservative.

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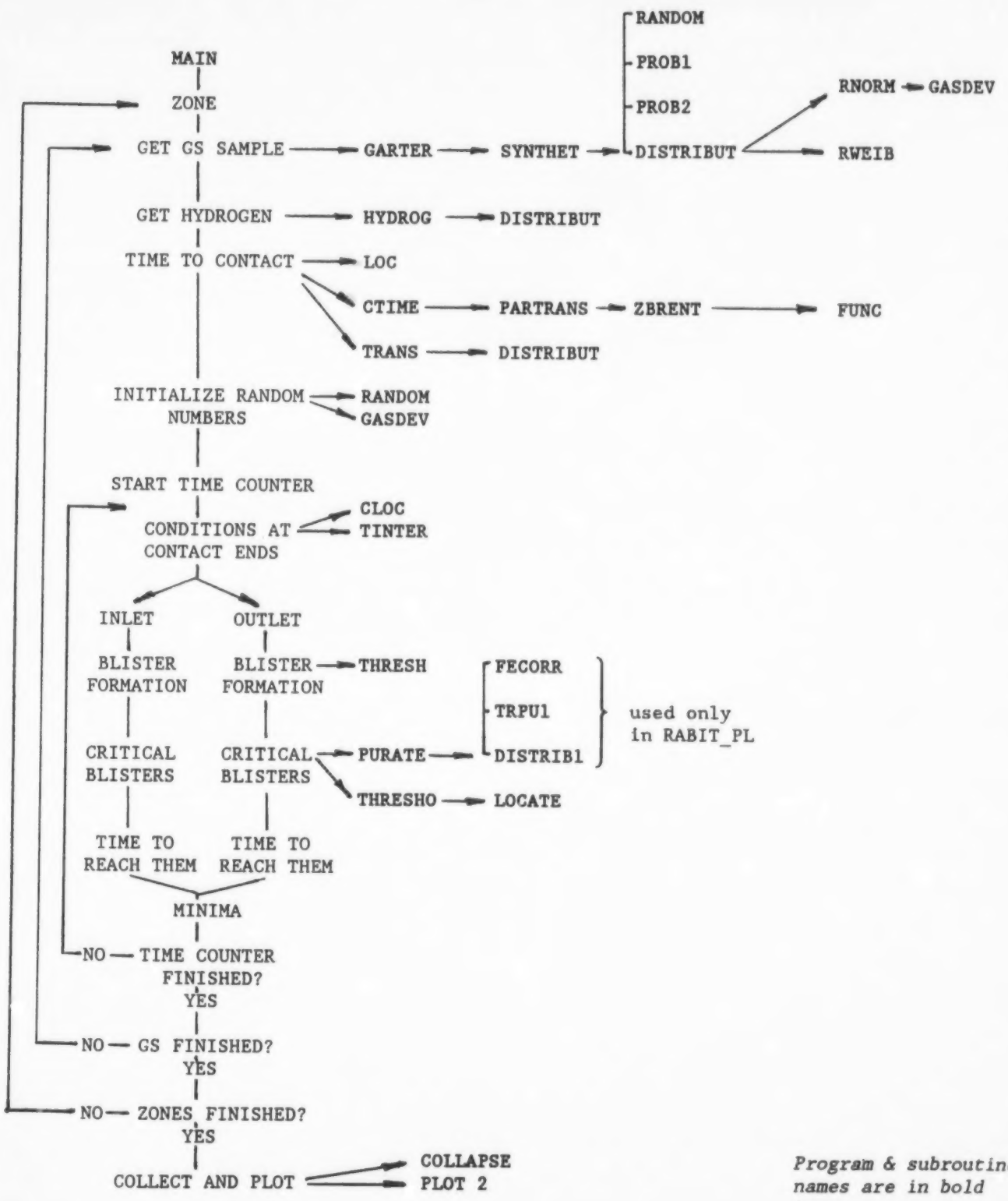
DVL/TPB/ML:ljc

FIGURE 1

STRUCTURE OF THE PROGRAM



Program & subroutine names are in bold type

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REFERENCES

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2. D.V. Leemans and M. Leger, "Assessment of Blister Formation in Pickering 3 and 4 Reactors", OHRD Report 87-6-K.

3. M. Leger, D.V. Leemans and T.P. Byrne, "Probabilistic Assessment of the Pickering Unit 4 Core for Pressure Tube Cracking Due to Hydride Blister Formation", OHRD Report 88-324-K.

APPENDIX 1

Development of the Threshold Hydrogen Levels Required for Critical blisters

A1.0 INTRODUCTION

This appendix describes the method by which hydrogen equivalent levels corresponding to critical blister sizes were established. The basis for the definition of a critical blister is reviewed. The blister fracture results from TRAC Task 415 and the predictions of growth based upon TRAC Task 411 work are used to produce the required threshold levels. Necessarily, there have been simplifications in the modelling as a complete description of blister growth was not yet ready for incorporation into the probabilistic computer model.

A1.1 Definition of Critical Size

For the purposes of establishing pressure tube life limits, critical blisters are considered to be blisters which can crack under operating stress to produce an initiation site for delayed hydride cracking (DHC). Since this definition appears to ignore the necessity for DHC to a critical crack size before a tube would rupture, a rationale for this definition of a critical blister is required. The main arguments in this rationale are as follows: 1. The temperature gradient through the wall of the pressure tube in the contact area would promote axial rather than radial growth of any cracks; 2. Initiation from multiple sources is likely in the case of pressure tube-calandria tube contact. Taken together these two factors argue against leak-before-break; 3. Pressure tubes are subjected to conditions, other than operating conditions, in which growth of cracks by DHC could not be ruled out. The presence of an active DHC crack would be of concern; and, finally, 4. The results of analysis of the Pickering 1 and 2 tubes removed following the G-16 incident indicate that there were no other tubes containing cracks to the blister boundary which could propagate by DHC. This latter point supports the thinking that it was initiation rather than propagation that determined the life limit for G-16.

In order to define a critical blister size, it is necessary to define what is meant by any blister size. Since blisters are a distribution of hydride, rather than simply solid hydride, blisters which appear to be similar in size metallographically may, in fact, be quite different. For this work, we have elected to use a specific definition of blister size which is the blister depth. In order to make comparisons between the depths calculated in blister growth modelling and the depths of blisters which would crack at a specific stress level, an "equivalent" blister depth has been defined which is the depth of a blister of solid hydride which has an equal weight fraction of solid hydride through the tube wall thickness as the blister being considered. This equivalent blister depth can be easily produced by the blister growth model. In order to determine equivalent depths for blisters actually tested to fracture, a relationship between profile height (maximum surface relief change associated with blister growth) and equivalent blister depth was established using results of measurements of the deuterium distributions in some deuterided blister samples. These results indicated that the equivalent blister depth was 7.3 times the observed profile height.

A1.2 Blister Fracture Results

A distinct correlation between the stress at which cracking first occurs in a blister in a four point bend test and the equivalent blister depth has been established for all the blisters grown using the air-jet method and tested to fracture at OHRD/1/. Figure A1 summarizes these

results. The results include both room temperature and elevated temperature tests on blisters grown under many different conditions. Initial statistical tests on these results have indicated that the different data sets obtained in various tests cannot be distinguished and therefore all the results can be considered as a single data set.

The lines on the figure represent the average predicted equivalent depth of a blister which would crack at a given applied stress as well as the upper and lower bound equivalent depths to 95% confidence based upon the data. This preliminary analysis yields a predicted average blister depth which would crack at 120 MPa (Pickering outlet stress) of 0.65 mm and a lower bound equivalent depth at 95% confidence of 0.46 mm.

These results have been combined with the output of the blister growth modelling (Appendix 2) to yield a table of thresholds (the example in Table A1 below is Pickering specific) which can be used to determine the critical bulk tube concentration required for a critical blister as a function of temperature of the PHT and the hydrogen pickup rate.

TABLE A1

CONCENTRATIONS REQUIRED TO FORM CRITICAL BLISTERS AS A FUNCTION OF PICKUP RATE AND PHT TEMPERATURE

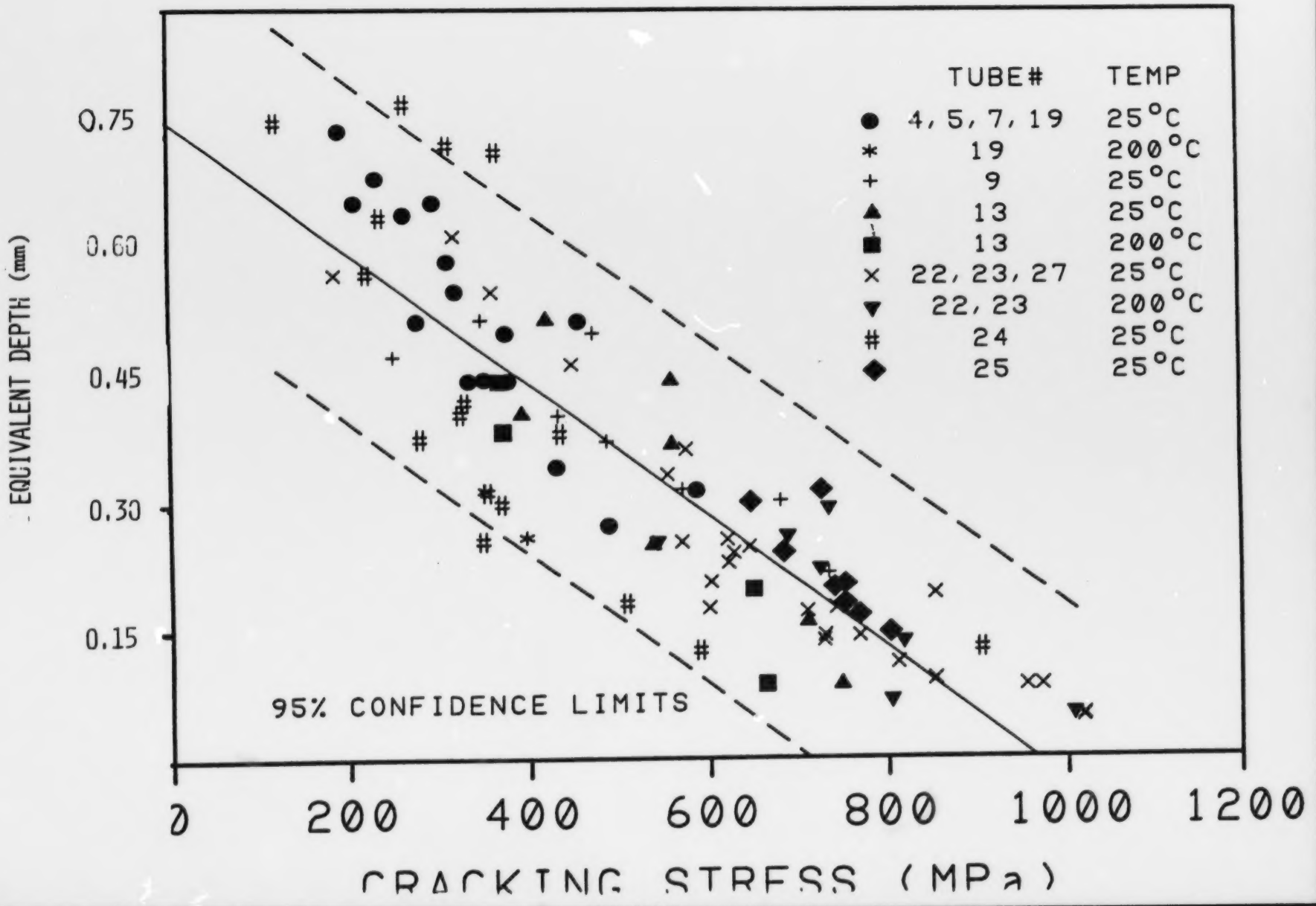
Pickup Rate (H Equiv./Year)	PHT TEMPERATURE (°K) 520.2	543.2	568.2
0	25.1 (1.30)	30.7 (1.50)	37.7 (1.90)
.8	33.5 (2.25)	37.1 (1.95)	42.5 (2.60)
4.	38.8 (2.15)	40.5 (2.18)	44.5 (2.45)
8	46.7 (2.7)	46.4 (2.6)	48.8 (2.7)
12	53.3 (3.35)	51.1 (2.9)	52.3 (2.9)
20	65.0 (4.8)	59.2 (3.6)	58.3 (3.35)
40	92.8 (9.0)	75.5 (5.3)	70.1 (4.35)

Note: Concentrations are in hydrogen equivalent ppm. Numbers in parentheses are the standard deviation estimate for the critical concentration.

Reference:

1. M. Leger, G.D. Moan, A.C. Wallace and N.J. Watson, "Growth, Fracture and Nondestructive Evaluation of Hydride Blisters in Zr-2.5 wt% Nb Pressure Tubes", Zirconium in the Nuclear Industry, Eighth International Symposium, ASTM STP1023, L.F.P. Van Swan and C.M. Eucken, Eds, (In press).

FIGURE A1


TUBE# TEMP
4, 5, 7, 19 25°C
19 200°C
9 25°C
13 25°C
13 200°C
22, 23, 27 25°C
22, 23 200°C
24 25°C
25 25°C
95% CONFIDENCE LIMITS
EQUIVALENT DEPTH (mm)
0.75
0.60
0.45
0.30
0.15
0
200
400
600
800
1000
1200
CRACKING STRESS (MPa)

APPENDIX 2

Blister Growth Modelling

A2.0 INTRODUCTION

The purpose of this appendix is to summarize some of the key features and assumptions of the blister growth model which is used to produce blister sizes as a function of either time or bulk concentration for use in the probabilistic assessment of critical blisters. The basis for the model as well as comparisons of the model with experimentally grown blisters has been previously documented/1,2,3,4/.

A2.1 Description of the Model

The program used to carry out the necessary predictions was the axisymmetric finite difference code. Since progress on this model was last reported, some modifications were introduced to the model to smooth out the blister growth as the blister grows through cell boundaries. This was accomplished by allowing the TSS for precipitation to be a continuous function of the volume fraction of hydride in the cells in which the blister was growing.

The basic assumptions in the model as it has been applied to the probabilistic work are as follows:

1. A single blister is modelled rather than an array of blisters. At low bulk hydrogen concentrations, a single blister will grow slightly faster than blisters with similar thermal boundary conditions in a closely spaced array because, in that case, the blisters will be competing for a finite amount of available hydrogen. However, as the bulk hydrogen level increases, the overlap of the diffusion fields of each blister in an array would diminish.

2. The deuterium diffusion coefficient has been used in the model for both the initial hydrogen and the deuterium picked up. The two isotopes are treated as a single species for diffusion purposes. Although it is possible to separate the treatment of the two species, the result cannot be made general to any tube because the amount of each isotope will be tube dependent. Use of the deuterium diffusion coefficient will result in small underestimates of blister size when most of the hydrogen equivalent in the tube is in the form of hydrogen rather than deuterium.

3. The depth of the blister predicted by the model is the "equivalent depth", ie, the depth of a blister of solid hydride (16000 ppm H) which would contain the same weight fraction of hydride (averaged through the wall thickness of the tube at the deepest part of the blister) as the actual blister.

4. The heat of transport of hydrogen has been taken to be 20900 joules/mole for the base case. This is based on some as yet unpublished results obtained at the University of Toronto over the last several years. These results, taken as a group, tend to indicate that the value of 25100 joules/mole used in the past is probably too large. The effect of using the lower value in the blister growth predictions is to shift the thresholds for particular blister sizes upwards by between 2 and 3 ppm.

5. The thermal boundary conditions at the contact where the blister grows are time independent in the model. A 5 mm diameter contact is assumed with a heat transfer coefficient of 10,000 $W/m^2°C$. The heat transfer coefficient of the annulus gas surrounding the contact area is dependent on the local gap between pressure tube and calandria tube. In these calculations this gap is assumed to be about half the height of a critical blister and therefore, an annulus gas heat transfer coefficient of 600 $W/m^2°C$ is used.

A2.2 **Observations on the Results**

The results shown in Figures A2.1 and A2.2 illustrate the model output for the base case scenario at a point in a Pickering channel where the PHT temperature is 270°C.

Blister growth versus time (Figure A2.1) shows that at high pickup rates, the blister growth can indeed be fast. When the results are plotted against bulk concentration, it is seen that lower pickup rates result in larger blisters at any particular bulk concentration. This is due to the fact that at low pick-up rates the blister growth is much closer to being an equilibrium phenomenon whereas at higher pickup rates, the bulk level increases faster than the blister can grow. These figures illustrate the significance of pickup rate information in the calculation of critical blister thresholds.

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1. T.P. Byrne, OHRD Report 84-30-H, February 1984.
2. T.P. Byrne and M. Leger, OHRD Report 85-29, September 1985.
3. T.P. Byrne, M.S. Gadala and M. Leger, "Hydrogen Redistribution Due to Temperature Gradients in Zirconium Alloys - a Finite Element Approach", Proceedings of the Eighth International Conference on Structural Mechanics In-Reactor Technology, Brussels, Belgium 1985.
4. M. Leger and T.P. Byrne, OH D&D Gen 85431, Fuel Channel Technology Seminar, November 1985.

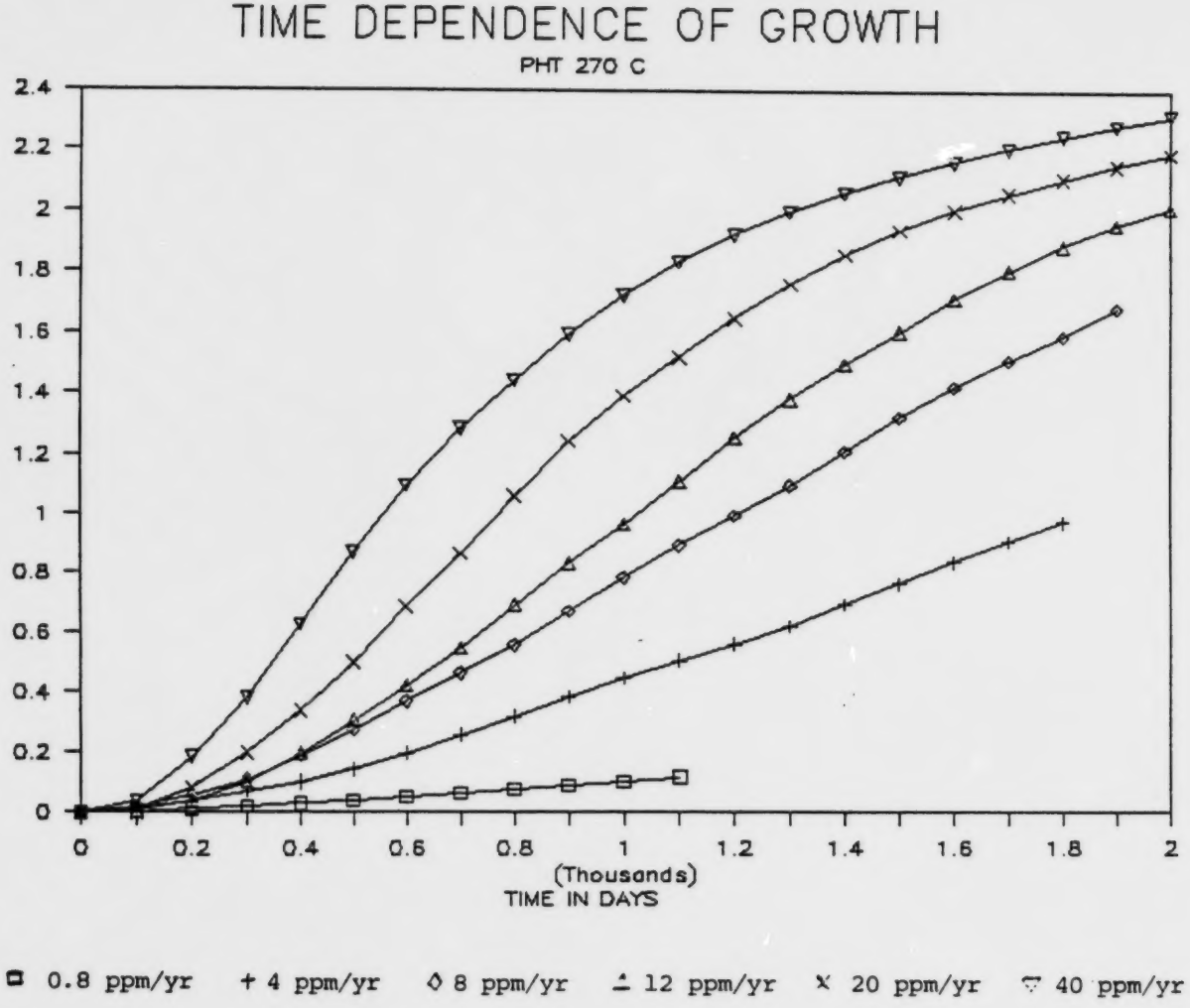
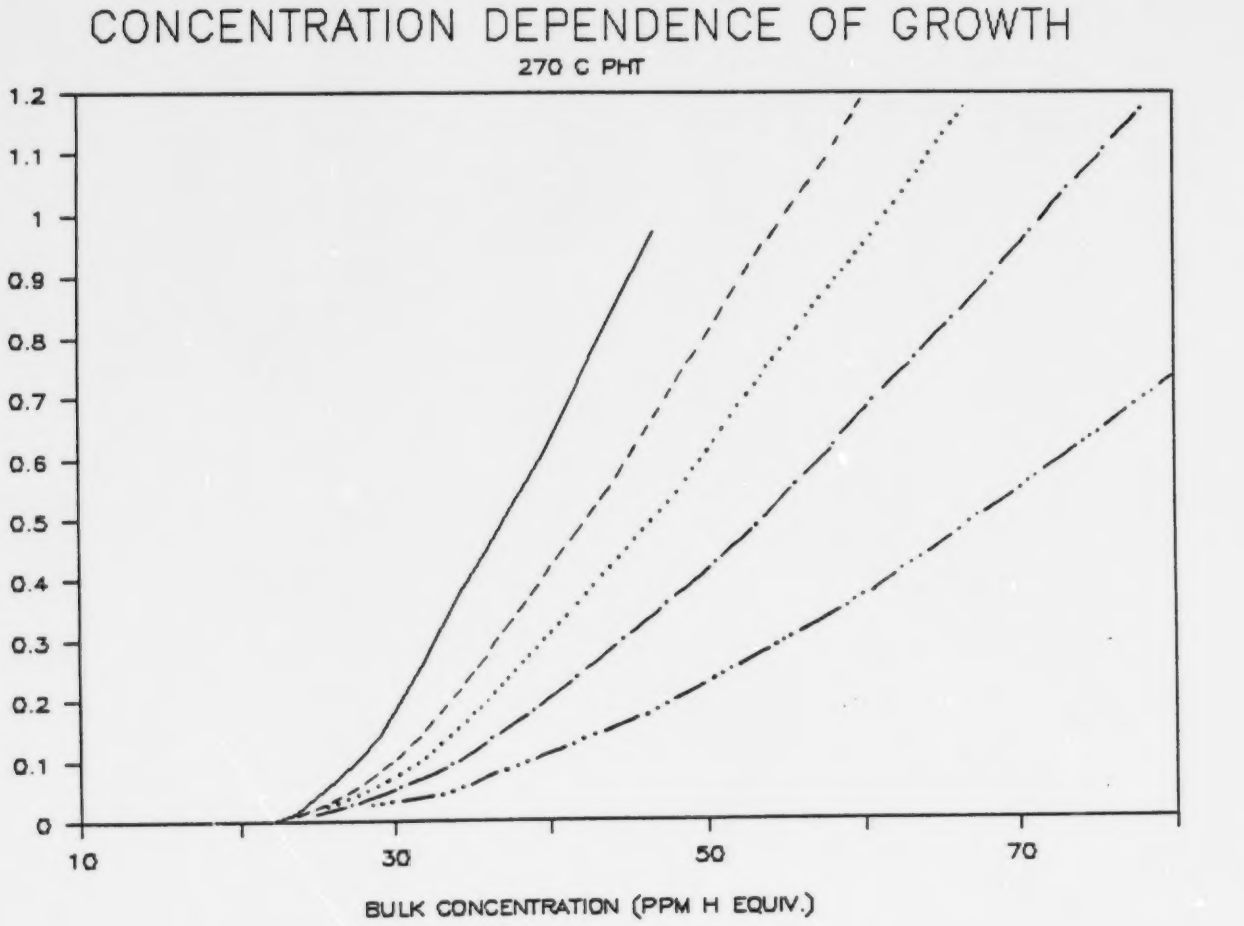

TIME DEPENDENCE OF GROWTH
PHT 270 C
DEPTH IN mm.
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
(Thousands)
TIME IN DAYS
0.8 ppm/yr
4 ppm/yr
8 ppm/yr
12 ppm/yr
20 ppm/yr
40 ppm/yr

FIGURE A2.1



____ 4 ppm/yr _ _ _ 8 ppm/yr .... 12 ppm/yr ____ . 20 ppm/yr ___.. 40 ppm/yr

FIGURE A2.2

APPENDIX 3

Treatment of Garterspring Locations

The current program allows for two types of inputs to generate a sample of garterspring locations:

1. A synthetic distribution similar to that described in Reference 1.

2. The data of the garterspring location measurements done at Pickering 3 and Pickering 4[1]

As noted elsewhere the garterspring location distribution does not follow a simple distribution/3/. Two of the problems noted are the observed large peaks in the distributions at the design locations and the asymmetry in the displacements. A method, which allows the construction of a distribution based on a set of measurements, was reported in Reference 1 and used with the new set of data. It involves the following steps:

1. Garterspring locations less or equal to 5 cm away from the design location are considered as design locations;

2. The convention to denote outboard as positive, inboard as negative, and design as zero is adopted;

3. For the purpose of generating a synthetic distribution the databases for Pickering 3 and Pickering 4 are merged;

4. A table containing directional probabilities for East and West inlets is established;

5. A correlation table between inlet and outlet garterspring movement is established to preserve the correlation in displacements;

6. The magnitude of the displacements are assumed to be Weibull distributed;

7. The parameters of the four Weibull distributions (inlet outboard and inboard, outlet outboard and inboard) are then calculated.

This cumbersome procedure results in a distribution which represents the data very well. A short computer program was written to carry out the necessary calculations. Figures A3.1, A3.2 and A3.3 show for the synthetic distribution (*) and the datasets (+) the cumulative probabilities of the inlets, the outlets and the central spanlength. The fit between the proposed distribution and the observed dataset is very good.

---

1. Due to the confusion in reported data, a review of all the measurements was undertaken by Mr. C. Schulte of CNS. His findings are reported in Reference 2 and are used as the database for this work.

In the development of this garterspring distribution the databases of Pickering 3 and Pickering 4 have been merged. It should be noted that in the authors' opinion there is a difference in the garterspring location distribution of Pickering 3 and 4. Therefore, the databases will be used as inputs in the model when the influence of the different garterspring locations of Pickering 3 and 4 on the model predictions are studied.

References

1. D.V. Leemans and M. Leger, "Assessment of Blister Formation in Pickering 3 and 4 Reactors", Ontario Hydro Research Report 87-6-K, 1987.

2. Memorandum of C.W. Schulte to M. Leger, Garterspring Displacements from Inspections in BNGS-A and PNGS-A, Units 3 and 4: Revision", File CNS 31110.1, X-NCCF-4.10, November 10, 1987.

3. Memorandum of M.W. Hardie to REFAB Task Force, "Preliminary Analysis of Pickering A Garter Positions/REFAB Assessment Work Package No. 10", File #907-N31100P, September 22, 1986.

34EAST 34WEST MATTEST

COMPARISON OF INLETS

SCALE=100

X	Y *	Y1 +	0	20	40	60	80	100
210.	16.	28.	*+					
200.	18.	28.	*+					
190.	19.	28.	*+					
180.	19.	28.	*+					
170.	24.	28.	*+					
160.	32.	28.	+					
150.	35.	28.	+					
140.	39.	28.	+*					
130.	44.	47.	*+					
120.	48.	66.	* +					
110.	51.	66.	* +					
100.	57.	66.	*+					
90.	62.	85.	* +					
80.	68.	85.	* +					
70.	84.	85.	*+					
60.	93.	85.	+					
50.	106.	85.	+ *					
40.	115.	103.	+ *					
30.	123.	103.	+ *					
20.	137.	103.	+ *					
10.	149.	148.	+					
0.	618.	379.	+			*		
-10.	791.	805.					* +	
-20.	881.	898.						* +
-30.	928.	944.						* +
-40.	957.	972.						* +
-50.	972.	972.						+
-60.	982.	972.						+*
-70.	987.	972.						+*
-80.	993.	972.						+ *
-90.	996.	1000.						*+
-100.	997.	1000.						*+
-110.	999.	1000.						*+
-120.	999.	1000.						*+
-130.	1000.	1000.						+
-140.	1000.	1000.						+
-150.	1000.	1000.						+
-160.	1000.	1000.						+
-170.	1000.	1000.						+
-180.	1000.	1000.						+
-190.	1000.	1000.						+
-200.	1000.	1000.						+
-210.	1000.	1000.						+
-220.	1000.	1000.						+
-230.	1000.	1000.						+
-240.	1000.	1000.						+
-250.	1000.	1000.						+
-260.	1000.	1000.						+
-270.	1000.	1000.						+
-280.	1000.	1000.						+

DISTANCE FROM DESIGN POSITION

CUMULATIVE PROBABILITY X1000

FIGURE A3.1

COMPARISON OF OUTLETS

X	Y *	Y1 +	0 SCALE=100 20 40 60 80 100
210.	20.	47.	* +
200.	27.	47.	* +
190.	34.	47.	*+
180.	44.	47.	+
170.	53.	47.	+*
160.	57.	66.	*+
150.	65.	66.	+
140.	72.	93.	* +
130.	75.	93.	* +
120.	76.	93.	* +
110.	78.	93.	* +
100.	78.	93.	* +
90.	79.	93.	*+
80.	80.	93.	*+
70.	80.	93.	*+
60.	80.	93.	*+
50.	80.	93.	*+
40.	80.	93.	*+
30.	80.	93.	*+
20.	80.	93.	*+
10.	80.	93.	*+
0.	588.	435.	+ *
-10.	720.	777.	* +
-20.	822.	841.	* +
-30.	885.	915.	* +
-40.	918.	915.	+
-50.	947.	934.	+*
-60.	968.	934.	+ *
-70.	974.	972.	+
-80.	983.	972.	+*
-90.	989.	1000.	* +
-100.	994.	1000.	*+
-110.	996.	1000.	*+
-120.	996.	1000.	*+
-130.	998.	1000.	*+
-140.	999.	1000.	*+
-150.	999.	1000.	*+
-160.	1000.	1000.	+
-170.	1000.	1000.	+
-180.	1000.	1000.	+
-190.	1000.	1000.	+
-200.	1000.	1000.	+
-210.	1000.	1000.	+
-220.	1000.	1000.	+
-230.	1000.	1000.	+
-240.	1000.	1000.	+
-250.	1000.	1000.	+
-260.	1000.	1000.	+
-270.	1000.	1000.	+
-280.	1000.	1000.	+

FIGURE A3.2

COMPARISON OF SPANLENGTHS

SCALE=100

X	Y *	Y1 +	0	20	40	60	80	100
10.	1000.	1000.						
20.	1000.	1000.						
30.	1000.	1000.						
40.	999.	1000.						
50.	999.	1000.						
60.	999.	1000.						
70.	996.	1000.						
80.	994.	1000.						
90.	989.	1000.						
100.	981.	981.						
110.	969.	981.						
120.	957.	934.						
130.	944.	934.						
140.	923.	915.						
150.	888.	915.						
160.	842.	915.						
170.	740.	805.						
180.	617.	640.						
190.	432.	298.						
200.	183.	205.						
210.	172.	177.						
220.	163.	177.						
230.	154.	159.						
240.	147.	159.						
250.	143.	159.						
260.	135.	159.						
270.	127.	159.						
280.	122.	140.						
290.	116.	140.						
300.	115.	140.						
310.	108.	140.						
320.	100.	93.						
330.	91.	93.						
340.	84.	74.						
350.	74.	74.						
360.	68.	47.						
370.	61.	47.						
380.	55.	19.						
390.	47.	19.						
400.	42.	19.						
410.	30.	19.						
420.	24.	19.						
430.	22.	19.						
440.	21.	19.						
450.	19.	19.						
460.	16.	19.						
470.	16.	19.						
480.	13.	19.						
490.	10.	19.						
500.	10.	19.						

SPANLENGTH

FIGURE A3.3

APPENDIX 4

Calculation of Contact Time and Initial Contact

The contact time and initial contact locations are calculated in this model based on the nomograms and information reported by Sakaguchi/1,2/. In his work Sakaguchi uses design creep rates for the pressure tube reported in CRNL-1993 and the ABAQUS code. Some small refinements to the equations in the report calculating the contact time were carried out in order to minimize the sum of the squares of the differences between observed and calculated times to contact (instead of the logarithm of these times).

The computer implementation of Sakaguchi's work is relatively straightforward. In order to test the proposed algorithm 113 test cases were calculated and the results compared with the results of the ABAQUS runs reported in Reference 1. This comparison (see Table 4.1) showed that the algorithm was very effective indeed. The contact times were mostly within 1.5 years (96% of the time) and within one node (98% of the time). In four cases the algorithm calculated the location and time of contact of the second contact due to the very small time difference between first and second contact.

In order to evaluate the importance of second contacts, a computer experiment was carried out in which those situations were flagged where second contacts were important. It should be noted that the database used to develop this flagging is again Reference 1. Its author claims, however that, the data on second contacts do not have the same reliability as the data on first contacts. In a thousand realizations thirty-one have second contacts before thirty years but only four have second contacts before twenty-years. Therefore, it was decided to ignore the second contacts as the error made for the time period of interest would be small.

The nomograms in Reference 1 are applicable only to the central core. For the intermediate and low flux channels the transformation factors derived from the work of V. Yu/3/ and reported elsewhere/4/ are used.

References

1. R.L. Sakaguchi, "Pickering NGS A, Units 3/4. Nomograms and Equations for Contact Predictions in High-Flux Fuel Channels", Ontario Hydro Design and Development Division - Generation Report No. 87/140, May 1987.

2. Memo from R.L. Sakaguchi to C.W. Schulte, "Contact Location Information for Nomograms Usage", July 8, 1987.

3. V.W. Yu, "Predictions of Pressure Tube to Calandria Tube Contact in PNGS A Unit 3 and 4, "Ontario Hydro Nuclear Systems Department, Report No. 84-3992, November 1984.

4. D.V. Leemans and M. Leger, "Assessment of Blister Formation in Pickering 3 and 4 Reactors", Ontario Hydro Research Report No. 87-6-K, 1987.

TABLE 4.1 - LEGEND

The table beginning on the next page has thirteen columns. The significance of the column labels is detailed below.

1. No - Number of simulation in Sakaguchi's report;
2. GS1 - Inlet garterspring displacement (in inches);
3. GS2 - Outlet garterspring displacement (in inches);
4. LOC - Area Location see Sakaguchi's map (calculated in our program);
5. TIME - Time to first contact (calculated in our program);
6. NODE - First contact location (calculated in our program);
7. LOC2 - For the second contact area location (zero where irrelevant);
8. TIME2 - Time to second contact (calculated but not used by us, zero is used when irrelevant);
9. NODE2 - Second contact location (calculated but not used by us, zero is used when irrelevant);
10. STIME - Time to first contact according to Sakaguchi;
11. SNODE - First contact location according to Sakaguchi;
12. STIME2 - Time to second contact according to Sakaguchi;
13. SNODE2 - Second contact location according to Sakaguchi.

TABLE 4.1

NO.	GS1	GS2	LOC	TIME	NODE	LOC2	TIME2	NODE2	STIME	SNODE	STIME2	SNODE2
1	-96.0	85.3	1	0.128	17.038	0	100.000	200.000	0	17		
2	-63.0	85.3	1	1.840	15.553	0	100.000	200.000	1.9	16		
3	-60.0	85.3	1	2.344	15.418	0	100.000	200.000	2.39	15		
4	-60.0	60.0	1	2.344	15.418	0	100.000	200.000	2.39	15		
5	-60.0	0.0	1	2.344	15.418	0	100.000	200.000	2.35	15		
6	-57.0	85.3	2	2.999	14.965	0	100.000	200.000	2.99	15		
7	-54.0	85.3	2	3.738	14.676	0	100.000	200.000	3.73	15		
8	-54.0	66.0	2	3.738	14.676	0	100.000	200.000	3.74	15		
9	-54.0	48.0	2	4.065	14.676	0	100.000	200.000	3.73	15		
10	-54.0	0.0	2	2.653	14.676	0	100.000	200.000	3.46	15		
11	-51.0	85.3	2	4.659	14.388	0	100.000	200.000	4.65	14		
12	-48.0	72.0	2	5.806	14.099	0	100.000	200.000	5.78	14		
13	-48.0	48.0	2	5.861	14.099	0	100.000	200.000	5.62	14		
14	-46.0	85.3	2	6.725	13.907	0	100.000	200.000	6.71	14		
15	-42.0	85.3	3	8.489	29.094	0	100.000	200.000	8.41	30		
16	-42.0	60.0	3	8.489	29.094	0	100.000	200.000	8.39	30		
17	-40.0	85.3	3	7.439	28.942	0	100.000	200.000	7.45	30		
18	-39.0	48.0	3	9.425	28.311	0	100.000	200.000	9.94	13	10.0	29
19	-36.0	60.0	3	5.712	28.636	0	100.000	200.000	5.59	29		
20	-35.0	85.3	3	5.347	28.560	0	100.000	200.000	5.25	29		
21	-33.0	48.0	3	6.151	27.853	0	100.000	200.000	7.53	28		
22	-30.0	60.0	3	3.843	28.178	0	100.000	200.000	3.82	28		
23	-30.0	36.0	3	12.706	26.540	0	100.000	200.000	14.63	27		
24	-30.0	33.0	2	15.366	12.368	3	16.068	26.269	15.19	12	18.0	27
25	-30.0	-12.0	2	10.300	12.368	6	14.773	31.672	11.3	13	16.7	31
26	-24.0	60.0	3	2.586	27.720	0	100.000	200.000	2.59	28		
27	-24.0	48.0	3	3.243	27.166	0	100.000	200.000	3.98	27		
28	-24.0	30.0	3	13.260	25.540	0	100.000	200.000	14.00	26		
29	-24.0	24.0	2	20.449	11.791	0	100.000	200.000	20.60	12		
30	-24.0	-12.0	2	14.848	11.791	6	15.726	31.672	14.86	12	16.8	31
31	-24.0	-48.0	6	1.356	28.324	0	100.000	200.000	3.14	28		
32	-21.0	85.3	3	2.121	27.491	0	100.000	200.000	2.15	28		

TABLE 4.1 (Cont'd)

NO.	GS1	GS2	LOC	TIME	NODE	LOC2	TIME2	NODE2	STIME	SNODE	STIME2	SNODE2
33	-21.0	24.0	3	17.130	24.769	0	100.000	200.000	17.62	25		
34	-21.0	21.0	3	21.661	24.498	0	100.000	200.000	22.81	25		
35	-18.0	85.3	3	1.740	27.262	0	100.000	200.000	1.75	27		
36	-18.0	72.0	3	1.740	27.262	0	100.000	200.000	1.74	27		
37	-18.0	24.0	3	13.838	24.540	0	100.000	200.000	13.69	25		
38	-18.0	21.0	3	17.499	24.269	0	100.000	200.000	17.51	25		
39	-18.0	18.0	3	22.128	23.998	0	100.000	200.000	22.79	24		
40	-18.0	-6.0	2	22.578	11.214	6	25.184	32.230	21.20	11	24.3	32
41	-18.0	-12.0	6	16.740	31.672	0	100.000	200.000	17.24	31		
42	-15.0	85.3	4	0.092	27.033	0	100.000	200.000	1.42	27		
43	-15.0	15.0	4	22.605	23.498	0	100.000	200.000	22.53	24		
44	-15.0	-6.0	6	25.983	32.230	0	100.000	200.000	24.90	32		
45	-12.0	85.3	4	0.075	26.804	0	100.000	200.000	1.15	27		
46	-12.0	48.0	4	1.381	26.250	0	100.000	200.000	1.80	26		
47	-12.0	12.0	4	23.093	22.998	0	100.000	200.000	22.69	23		
48	-12.0	9.0	4	29.201	22.727	0	100.000	200.000	29.90	23		
49	-12.0	-6.0	6	26.808	32.230	0	100.000	200.000	25.70	32		
50	-11.8	0.0	2	34.732	10.619	0	100.000	200.000	34.47	11		
51	-11.5	3.0	2	36.351	10.589	0	100.000	200.000	37.38	10		
52	-11.5	-3.0	6	33.053	32.509	0	100.000	200.000	32.32	32		
53	-11.2	-28.2	6	5.967	30.166	0	100.000	200.000	7.94	30		
54	-9.0	3.0	4	37.722	21.956	0	100.000	200.000	N/C			
55	-9.0	0.0	2	41.221	10.349	0	100.000	200.000	N/C			
56	-9.0	-3.0	6	33.925	32.509	0	100.000	200.000	33.66	32		
57	-6.0	18.0	4	9.425	23.082	0	100.000	200.000	8.84	23		
58	-6.0	12.0	4	15.071	22.540	0	100.000	200.000	13.97	23		
59	-6.0	6.0	4	24.099	21.998	0	100.000	200.000	23.22	22		
60	-6.0	3.0	4	30.474	21.727	0	100.000	200.000	30.85	22		
61	-6.0	0.0	4	38.535	21.456	0	100.000	200.000	N/C			
62	-6.0	-3.0	6	35.002	32.509	0	100.000	200.000	35.48	33		
63	-6.0	-6.0	6	28.536	32.230	0	100.000	200.000	27.66	32		
64	-5.3	-0.7	4	38.786	21.340	0	100.000	200.000	N/C			

TABLE 4.1 (Cont'd)

NO.	GS1	GS2	LOC	TIME	NODE	LOC2	TIME2	NODE2	STIME	SNODE	STIME2	SNODE1
65	-3.9	-0.6	4	34.767	21.236	0	100.000	200.000	35.62	21		
66	-2.9	-7.4	6	26.875	32.103	0	100.000	200.000	26.07	32		
67	-2.7	-2.9	6	36.456	32.517	0	100.000	200.000	37.88	33		
68	-2.6	3.2	4	23.643	21.488	0	100.000	200.000	22.68	22		
69	-2.3	-2.8	6	36.793	32.525	0	100.000	200.000	38.48	33		
70	-2.2	0.4	4	28.504	21.202	0	100.000	200.000	28.37	21		
71	-1.6	-0.8	4	29.905	21.054	0	100.000	200.000	29.88	21		
72	-1.6	0.0	4	28.121	21.118	0	100.000	200.000	27.93	21		
73	-0.6	-0.6	4	27.475	20.983	0	100.000	200.000	26.87	21		
74	0.0	85.3	4	0.032	25.888	0	100.000	200.000	0.4	26		
75	0.0	5.9	4	15.840	21.532	0	100.000	200.000	14.64	22		
76	0.0	0.0	4	25.150	20.998	0	100.000	200.000	24.33	21		
77	0.0	-3.0	4	31.803	20.727	0	100.000	200.000	32.79	21		
78	0.0	-4.8	6	33.052	32.345	0	100.000	200.000	33.57	32		
79	0.0	-28.2	6	6.707	30.166	0	100.000	200.000	8.06	30		
80	0.8	-8.5	6	25.894	32.001	0	100.000	200.000	25.25	32		
81	3.0	-6.0	6	31.340	32.230	0	100.000	200.000	31.83	32		
82	6.8	-4.1	4	21.399	20.112	0	100.000	200.000	20.44	20		
83	9.0	-9.0	4	26.812	19.498	6	27.199	31.951	27.30	32	27.4	19
84	12.0	85.3	4	0.014	24.972	0	100.000	200.000	0.04	25		
85	12.0	-6.0	4	17.130	19.540	0	100.000	200.000	16.38	19		
86	12.0	-12.0	4	22.879	31.672	0	100.000	200.000	22.56	32		
87	15.0	-12.0	4	22.128	18.769	6	23.605	31.672	22.78	18	23.4	32
88	16.7	-2.4	4	9.259	19.508	0	100.000	200.000	8.83	19		
89	18.0	-12.0	4	17.876	18.540	6	24.354	31.672	17.90	18	23.2	32
90	18.0	-15.0	6	19.855	31.393	0	100.000	200.000	19.66	31		
91	18.0	-18.0	6	16.188	31.114	0	100.000	200.000	15.85	31		
92	24.0	85.3	4	0.006	24.056	0	100.000	200.000	0.006	24		
93	24.0	-12.0	4	11.667	18.082	6	25.924	31.672	11.64	18		

TABLE 4.1(Cont'd)

NO.	GS1	GS2	LOC	TIME	NODE	LOC2	TIME2	NODE2	STIME	SNODE	STIME2	SNODE2
94	24.0	-15.0	4	14.753	17.811	6	21.136	31.393	15.23	17	20.1	32
95	24.0	-18.0	6	17.231	31.114	0	100.000	200.000	16.87	31		
96	27.0	-15.0	4	9.425	17.853	6	26.747	31.672	9.95	18		
97	27.0	-15.0	4	11.919	17.582	6	21.806	31.393	12.24	17	22.8	32
98	30.0	-12.0	4	7.614	17.624	6	27.596	31.672	7.90	17	22.7	32
99	30.0	-18.0	5	12.176	17.082	6	18.343	31.114	12.98	17	17.2	31
100	37.0	-24.0	5	11.834	16.006	6	13.114	30.556	12.88	31	13.6	15
101	40.0	-24.0	5	9.560	15.777	6	13.530	30.556	11.08	15		
102	42.0	-18.0	5	5.186	16.166	6	20.784	31.114	5.94	16		
103	42.0	-24.0	5	8.293	15.624	6	13.815	30.556	9.64	15		
104	45.0	-21.0	5	5.298	15.666	6	17.483	30.385	6.23	15		
105	48.0	72.0	4	0.003	22.224	0	100.000	200.000	0.0	20		
106	48.0	-12.0	4	2.117	16.250	0	100.000	200.000	2.65	16		
107	48.0	-18.0	5	3.385	15.708	6	22.124	31.114	4.17	15		
108	48.0	-30.0	5	8.654	14.624	6	9.775	29.998	9.63	30		
109	48.0	-72.0	7	0.521	26.092	0	100.000	200.000	0.51	26		
110	46.5	83.3	4	0.001	22.342	0	100.000	200.000	0.0	21		
111	50.0	-32.0	6	8.710	29.812	0	100.000	200.000	8.63	30		
112	60.0	-16.0	4	1.233	15.430	0	100.000	200.000	3.55	15		
113	60.0	-30.0	5	7.237	14.743	0	100.000	200.000	7.22	14		

APPENDIX 5

Modelling Contact Spreading

(R.A. Holt)

A functional relationship for contact spreading was derived from CDEPTH calculations. Parameters were then selected to give a fit to five available sets of contact length data with initial contact locations and times based on the existing probabilistic model.

The spread of contact is taken to consist of two components, an initial rapid stage, during which a considerable amount of elastic spreading occurs, followed by a slow spread of contact governed by creep.

In the model, the initial, rapid, spread of contact is taken directly from CDEPTH calculations of the extent of contact after 10,000 EFPH. This is given by:

$$S = S_0(t/10)^{\alpha}.\ell_0$$

where: S is the half length of contact (ie, the distance between the furthest extent of contact and the initial contact location),
S_0 is the half length of contact after 10,000 EFPH,
t is the time since contact in 1000's of EFPH,
ℓ_0 is the initial unsupported half length (ie, the distance from the point of initial contact to the next support),
α is a constant,

and: $S_0 = b\ell_0^{q}$

where: b and q are constants whose values depend on whether the next support is a spacer or the endfitting.

The later creep controlled spread of contact is assumed to occur at a rate:

$$dS/dt = -d\ell/dt = K\ell^{n}$$

where: ℓ is the current unsupported half length.

and hence:

$$S = \ell_0 - (K^{\iota}t^{\iota} + \ell^{\iota}_0{}^{m})^{1/m}$$

where: n is a constant,
$m = 1 - n$,
K is a constant,
$K^{\iota} = -m.K$,
$\ell_0^{\iota} = \ell_0 - S_0$,
$t^{\iota} = t - 10$.

According to the CDEPTH calculations, n has a value of about 5, and this depends on the location relative to the inlet, on whether the contact is spreading towards a spacer or an end fitting, on the orientation of the pressure tube, on the flux and temperature profiles etc. However, in comparisons with measured contacts for the five channels cited above, constant values of n and K gave a good fit to the data.

APPENDIX 6

Deuterium Pickup Rates

A6.0 INTRODUCTION

Over the last year a number of measurements of deuterium pickup in Pickering pressure tubes were taken which allows for a more realistic modelling of the deuterium uptake that these tubes experience. The estimates of pickup rates remain highly speculative. Therefore, two significantly different kinds of models are allowed to be used.

Model 1 - The Piece-wise linear model

A piecewise linear deuterium pickup model outlined in previous reports is postulated:

$$\text{Deut}(t) = pu_1 * \text{Transt} + pu_2 * (t - \text{Transt}) \qquad t > \text{Transt}$$
$$\text{Deut}(t) = pu_1 * t \qquad t < \text{Transt}$$

Where Deut (t) = total deuterium pickup
pu_1 = early pickup rate
Transt = Transition time
pu_2 = final pickup rate

Model 2 - The Databased Model

A power relationship with time is assumed.

$$\text{Deut}(t) = A\, t^n$$

These two types of models give the user a wide range of flexibility and allow sensitivity studies to be carried out. The two model types will now be discussed in more detail.

A6.1 Model 1 - The Piecewise Linear Model

Model 1 requires input on the three relevant parameters, primary pickup rate (pu_1), secondary pickup rate (pu_2), and transition time (Transt). All three parameters can be dependent on iron content (linearly) and are dependent on temperature (and therefore also position along the pressure tube). These last dependencies can take three forms: Arrhenius type, linear and piecewise linear.

There are two final options available in this model. The first one allows for an explicit dependence of transition time on primary pickup. The idea behind this is that with higher primary pickup rate the transition threshold may be reached earlier. The formal dependence of transition time on pu_1 can be chosen to be linear or inversely proportional.

The second option is to make the secondary pickup rate correlated with the primary pickup rate based on the assumption that the same basic processes underlie both the primary and secondary pickup rates.

It is understood that the two pickup rates and the transition time are random variables. The user provides the distribution type (normal, lognormal, Weibull) and the mean and the standard deviation at a reference temperature. The computer calculates the required parameters by the method of matching the moments.

A6.2 Model 2 - The Databased Model

The second model type for deuterium pickup is a power relationship with time. This method is directly databased. A file containing all the deuterium pickup data is set up. When the deuterium pickup at a particular position or temperature and time is required, the following steps are carried out.

1. A dataset of deuterium measurements (including time and position or temperature along the pressure tube) is read in from the datafile.

2. An interpolation (linear, polynomial/cubic splines) is done which yields the total deuterium pickup at the location or temperature of interest at the time of measurement.

3. The particular A value of the equation is calculated (the user must supply the n value).

4. The equation is now completely defined and both total pickup and pickup rate at this location or temperature can be calculated for any time.

The advantage of this model is that it uses all the observations up to now.

APPENDIX 7

Calculations for Probabilities, Reliabilities and Other Estimates

1. Calculation of the estimate of the probability of critical blister formation.

The best estimation of this probability is

$$\hat{p} = \frac{N_{cb}}{N_{TOT}}$$

where N_{cb} : is the number of realizations with critical blisters

N_{TOT} : is the number of realizations.

The variance on this estimate due to the number of Monte Carlo simulations.

$$\text{var } p = \frac{\hat{p}\ (1 - \hat{p}\ )}{N_{TOT}}$$

2. Calculation of the number of critically blistered tubes. If the central core contains N_{tubes} (with equal East and West tubes) then the average number of critically blistered tubes is:

$$< N_b > = \frac{N_{tubes}}{2} \qquad [\hat{p}_{EAST} + \hat{p}_{WEST}]$$

The variance is calculated using the relationships var (A+B) = var A + var B if A and B are mutually independent. Therefore, the variance on the east inlet and west inlet channels can be calculated independently.

There are two sources for the variance.

1. The number of critically blistered channels (N_b) in a number of channels (N) is binomially distributed with the probability of being critically blistered given by p_{cb}.
2. Since p_{cb} itself is not perfectly known, this uncertainty will contribute to the variance of the number of critically blistered tubes.

Using the relationship:

$$\text{var } y = E[\text{var } (y/x)] + \text{var } [E(y/x)]$$

where E stands for the expectation operator

we calculate

$$\text{var } N_b = E[Np\ (1-p)] + \text{var } [Np]$$

$$\text{var } N_b = E\,[Np - Np^2] + N^2 \text{var } p$$

$$\text{var } N_b = E[Np] - NE\,[p^2] + N^2 \text{var } p$$

$$\text{var } N_b = N\hat{p} - N \text{ var } p - N\hat{p}^2 + N^2 \text{var } p$$

$$\text{var } N_b = N\hat{p}\,(1-\hat{p}) + N\,(N-1) \text{ var } p$$

Now since we have shown above that $\text{var } p = \dfrac{\hat{p}(1-\hat{p})}{N_{TOT}}$

$$\text{var } N_b = N\hat{p}\,(1-\hat{p}) \qquad \left[1 + \frac{N-1}{N_{TOT}}\right]$$

Therefore, this indicates that the uncertainty on the number of blistered tubes in the central core increases with the number of channels in the core and also is crucially dependent on the ratio of channels in the core to the number of Monte Carlo realizations. In most of our work this correction term is held very small, as typically N-1 is around 100 and N_{TOT} around 5000.

3. The reliability of the central core is defined as the probability that none of the tubes in the central core have a critical blister.

The reliability of the central core comprising of N tubes is therefore defined as:

$$R = (1-p_1)\,(1-p_2) \ldots (1-p_N) = \prod_{i=1,n} (1-p_i)$$

where p_i is the probability of a critical blister in the ith tube.

The events in the N tubes are considered random, and the p_i are independent samples from a probability density distribution f(p) with a mean $\bar{p}$ and variance var p. These assumptions together with the relationship var (AB) = $\bar{B}^2$ var A + $\bar{A}^2$ var B + var A var B (A,B independent) allow us how to calculate the mean (R) and the variance of the reliability (var R).

$$E(R) = \bar{R} = \iiint (1-p_1)\,f(p_1) \ldots (1-p_n)\,(p_n)\,dp_n \ldots dp_1$$

$$= (1-\bar{p}_E)\,(1-\bar{p}_W) \ldots = (1-p_E)^{N/2}\,(1-p_W)^{N/2}$$

The variance will be calculated only for the east channels (n_E)

$$\text{var } R = E\,[(R-E(R))^2] = E\,[\Pi(1-p_i)^2 - (1-\bar{p})^{2n_E}] = E[\Pi(1-p_i)^2] - (1-\bar{p})^{2n_E}$$

$$E\,(\Pi(1-p_i)^2 = \iiint (1-p_1)^2\,f(p_1) \ldots (1-p_n)^2\,f(p_n)\,dp_n \ldots dp_1$$

Now the integral

$$\int (1-p_1)^2 f(p_1)\, dp_1 = \int (1-2p_1 + p_1^2) f(p_1)\, dp_1 = 1-2\bar{p} + p^2 + \text{var } p$$

Using this formulation

$$\text{var } R = [(1-p)^2 + \text{var } p]^{n}E - [(1-p)^2]^{n}E$$

Now var $p = \dfrac{\bar{p}(1-\bar{p})}{N_{TOT}}$

$$\text{var } R = (1-p)^{2n}E \quad \left[\left(1 + \frac{\bar{P}}{(1-\bar{p})N_{TOT}}\right)^{n_E} - 1\right]$$

$$\simeq (1-\bar{p})^{2n}E \left[\frac{n_E \quad \bar{p}}{N_{TOT} \quad (1-\bar{p})}\right]$$

$$\frac{\text{var } R}{R^2} = \left[\frac{n_E \quad (\bar{p})}{N_{TOT} \quad 1-\bar{p}}\right]$$

which in our work is held small (typically $< \left(\frac{1}{50}\right)^2$)

APPENDIX 8

Input Files

The program accesses two kinds of input files:

a. The Master Input File queued up on Unit 11 which controls the execution of the program;

b. Secondary input files related to specific inputs.

and generates two output files:

a. A general output file which describes in detail the used inputs and provides line plots of the results.

b. A database output file which can be used to provide more sophisticated plotting (DISPLAY) and which can be imported in such programs as LOTUS-1-2-3.

In the following, the structure of the input files will be explained. The master input file for the databased pickup rates is called INP_RABIT_DB and queued up on unit 11. It consists usually of thirty-four lines (see Table 8.1)

Line 1: Name of Reactor Unit/Number of zones to be evaluated.

Line 2: Name of general output file.

Line 3: Name of data output file.

Line 4: Input on the contact type scenario. Radius of contact/heat transfer coefficient at contact/heat transfer coefficient in the annulus gas.

Line 5: NRAND: if NRAND = 1 the initial seed for the random numbers are obtained via a time call;
if NRAND = 0, the initial seed is fixed.

Line 6: NINTERP: if NINTERP = 1, then the interpolation related to deuterium pickup is based on temperature;
if NINTERP = 0, then this interpolation is based on position.

Line 7: Name of the zone (Central, Intermediate, Outer)/
Number of tubes in the zone.

Line 8: Number of Monte Carlo realizations.

Line 9: Name of the temperature file/number of datasets on this file.

Line 10: KTYP/SDTEMP

KTYP (1,2, or 3) determines the temperature distribution (normal, lognormal or Weibull).
SDTEMP is the standard deviation of the temperature in degrees.

Line 11a: NTYP1/FNEAST/FNWEST/FNSYNTH

NTYP1 = 1, the garterspring information is databased;
NTYP1 ≠ 1: a synthetic distribution will be used.
FNEAST is the datafile with east inlet garterspring displacement
FNWEST is the datafile with west inlet garterspring displacement
FNSYNTH is the datafile containing the parameters of the synthetic distribution.

Line 11b: If NTYP = 1 then the next line has NUMEAST/NUMWEST.
NUMEAST = the number of datasets in FNEAST
NUMWEST = the number of datasets in FNWEST

Line 12: MTYP/SDTIME
MTYP (1,2 or 3) determines the time of contact distribution (normal, lognormal or Weibull)
SDTIME is the ratio of the standard deviation to the mean for the contact time.

Line 13a: NTYP2/FNHYDR
NTYP2 = 0 hydrogen distribution is databased
= 1 hydrogen distribution is normal
= 2 hydrogen distribution is lognormal
= 3 hydrogen distribution is Weibull

FNHYDR is the hydrogen database

b: If NTYP2 = 0 then the next line has NUMHYD
NUMHYD is the number of datasets on FNHYDR

c: If NTYP2 ≠ 0 then the next line has MEAN/SD/OFFSET
MEAN: Average hydrogen
SD: Standard deviation
OFFSET: Cutoff Value

Line 14: FNPICKUP: Hydrogen pickup datafile

Line 15: KINT/POLY
KINT = 1 Linear Interpolation for hydrogen - (location or temperature) relation
KINT = 2 Polynominal/Cubic Spline Interpolation
POLY = Time exponent

Line 16: NUMPU: Number of datasets on FNPICKUP

Line 17: HVALVE/QSTAR/CTP used in calculation of the threshold for blister formation

Line 18: Reference temperatures (3) for the threshold table in °K.

Line 19: Reference pickup rates (5) for the threshold table.

Line 20-26: Mean threshold (3 x 7) table for critical blisters.

Line 27-33: Standard deviation (3 x 7) table for the threshold of critical blisters.

Line 34: INTERCEPT/SLOPE

Relation of contact temperature to PHT temperature
Contact temperature = intercept + slope x PHT Temp.

If more than one zone is evaluated then Lines 7 to 34 have to be repeated.

The other master input file called INP_RABIT_PL applies for the piecewise linear hydrogen pickup scenario and is given in Table 8.2. A line by line description follows:

Line 1: Reactor Unit/Number of zones to be evaluated.

Line 2: Name of general output file.

Line 3: Name of data output file.

Line 4: Radius of contact/heat transfer coefficient at contact/heater transfer coefficient in the annulus gas.

Line 5: NRAND; if NRAND = 1, Randomization via time call
NRAND = 0, Randomization fixed.

Line 6: One (central, intermediate or outer)/Number of tubes in the zone.

Line 7: Number of realizations.

Line 8: TEMPERATURE FILE/Number of data sets in this file.

Line 9: KTYP/SDTEMP
KTYP (1,2 or 3) → temperature distribution (normal, lognormal or Weibull)
SDTEMP → standard deviation of temperature (degrees K)

Line 10a: NTYP1/FNEAST/FNWEST/FNSYNTH
NTYP1 = 1: Garterspring information are databased
NTYP1≠1: Synthetic distribution will be used
FNEAST: Datafile with east inlet garterspring displacements
FNWEST: Datafile with west inlet garterspring displacements
FNSYNTH: Datafile with parameters for the synthetic distributions

Line 10b: if NTYP1=1 then the next line contains NUMEAST, NUMWEST
NUMEAST = number of datasets in FNEAST
NUMWEST = number of datasets in FNWEST

Line 11: MTYP/SDTIME

MTYP (1,2 or 3) → time to contact (normal, lognormal or Weibull)
SDTIME is the ratio of standard deviation to mean of the contact time.

Line 12a: NTYP2/FNHYDR
NTYP2 = 0 Hydrogen distribution is databased
= 1 Hydrogen distribution is normal
= 2 Hydrogen distribution is lognormal
= 3 Hydrogen distribution is Weibull
FNHYDR is the hydrogen database

Line 12b: If NTYP2 = 0 then the next line has NUMHYD
NUMHYD is the number of datasets in FNHYDR

Line 12c: If NYTP2 ≠ 0 then the next line has the mean, standard deviation and cutoff of the hydrogen distribution.

Line 13: Indicates the type of distribution (normal, lognormal or Weibull) for the primary pickup (PPU) transition time (TT) and secondary pickup (SPU).

Line 14: Means of PPU, TT and SPU.

Line 15: Standard deviation of PPU, TT and SPU.

Line 16: Offset of PPU, TT and SPU.

Line 17: NTRANS (1) and NTRANS (2).

If NTRANS (1) = 0 then TT is independent of PPU
= 1 then TT is linearly dependent on PPU
= 2 then TT is inversely dependent on PPU
If NTRANS (2) = 0 then SPU is independent of PPU
= 1 then PPU is correlated with PPU

and one extra line with the correlation coefficient has to be read in.

Line 18: NTEMP(1), NTEMP(2), NTEMP(3). These indicate the type of temperature dependence of the three variables
1 indicates ARRHENIUS, 2 = LINEAR, 3 = PIECEWISE LINEAR

Line 19: ATEMP(1)/ATEMP(2)/ATEMP(3)
These are the reference temperatures for the three variables PPU, TT and SPU.

Line 20: BTEMP(1)/BTEMP(2)/BTEMP(3)
Describes the temperature dependence for the three variables PPU, TT and SPU (activation energy for Arrhenius slope for linear and piecewise linear).

Line 21: CTEMP(1)/CTEMP(2)/CTEMP(3)

Only used for piecewise linear; indicates the lower limit of the linear dependence of the variables on temperature.

Line 22: NIRON(1), NIRON(2), NIRON(3)
If NIRON(K) = 0 then the Kth variable is independent of iron
= 1 Kth variable is dependent on iron.

Line 22b: If any of the NIRON values is non zero then the two following lines are:

AIRON(1)/AIRON(2)/AIRON(3)
BIRON(1)/BIRON(2)/BIRON(3)

These coefficients are used in calculating an iron-sensitive parameter.
If any of these NIRON values is two, then the next line contains:

FNIRON: file with iron values and the next line contains:

NUMIRON: the number of datasets in FNIRON

If NIRON (1) is 1 then the next line is

NTYP3 (4): (1,2,3) → (normal, binormal, Weibull) followed by:

MEAN, STANDARD VARIATION, OFFSET of the iron distribution.

Line 23: HVALVE/QSTAR/CTP

Line 24: Reference temperatures (3) for the threshold table in °K.

Line 25: Reference pickup rates (5) for the threshold table.

Line 26-32: Mean threshold (3 x 7) table for critical blisters.

Line 33-39: Standard deviation (3 x 7) table for the threshold of critical blisters.

Line 40: INTERCEPT/SLOPE
Relation of contact temperature to PHT temperature.
Contact temperature = Intercept + slope x PHT temperature.

If more than one zone is evaluated then lines 6 to 40 have to be repeated.

The structure of the secondary files is as follows:

1. TEMPFILE (Table 8.3). The structure of the file is straightforward in that each line contains a location along the pressure tube and the temperature in degrees Kelvin.

2. FNSYNTH (Table 8.4). Consists of five lines, the first three lines describing the relevant probabilities and the last two lines describing the parameters of the Weibull distribution, as shown below.

	EAST INLETS	WEST INLETS	POSITIVE INLETS	DESIGN INLETS	NEGATIVE INLETS	
Line 1						Positive
Line 2						Design
Line 3						Negative

Line 4: Scale factors for positive inlets, negative inlets, positive outlets, negative outlets

Line 5: Shape factors for positive inlets, negative inlets, positive outlets, negative outlets.

3. FNEAST (Table 8.5). Consists of the inspection data for the garterspring locations. One line consists of /Tube Name/Inlet G/S displacement in meters/Outlet G/S displacement in meters.

4. FNPICKUP (Table 8.6). Data on hydrogen pickup.

Line 1: /Name of tube/time of measurements/number of measurements N_{meas}.

Line 2	Location	Temperature	Hydrogen Equivalent Picked up
.	.		.
.	.		.
.	.		.
Line $N_{meas}+1$	next tube		

5. FNHYDR: Data on initial hydrogen. Each line consists of one datapoint.

TABLE 8.1

STRUCTURE OF INP_RABIT_DB

```
'PICKERING 3' 1
'P3POW2'
'P3POW21'
2.50 0.010 .006
1
1
'CENTRAL' 184
10000
'PICK_TEMP1' 25
2 2.
1  'GS_3_EAST' 'GS_3_WEST' 'GS_3_SYN'
11 9
2 0.25
3  'DUMMY'
7.94 3.14 3.5
'P3_PU_CENT'
1 2.
13
28000. 20900. 41000.
520.2 543.2 568.2
0. 1. 5. 10. 15. 25. 50.
25.1 30.7 37.7
33.5 37.1 42.5
38.8 40.5 44.5
46.7 46.4 48.8
53.3 51.1 52.3
65.0 59.2 58.3
92.8 75.5 70.1
1.3 1.5 1.9
2.25 1.95 2.6
2.15 2.18 2.45
2.7 2.6 2.7
3.35 2.9 2.9
4.8 3.6 3.35
9.0 5.3 4.35
140.98 0.631
```

TABLE 8.2

STRUCTURE OF INP_RABIT_PL

```
'PICKERING 4' 1
'TEST'
'TEST1'
2.50 0.010 .006
1
'CENTRAL' 184
10000
'PICK_TEMP' 37
2 2.
2 'GS_34_EAST' 'GS_34_WEST' 'GS_34_SYN'
2 0.25
3 'DUMMY'
6.6 3.0 0.
1 2 3
0.40 13.00 1.84
0.17  1.3  1.34
0.00  0.00 0.00
0 0
1 1 3
567. 567. 555.2
5340. 0. .0783
  0.   0. 555.2
0 0 0
28000. 20900. 41000.
520.2 543.2 568.2
0. 1. 5. 10. 15. 25. 50.
25.1 30.7 37.7
33.5 37.1 42.5
38.8 40.5 44.5
46.7 46.4 48.8
53.3 51.1 52.3
65.0 59.2 58.3
92.8 75.5 70.1
1.30 1.50 1.90
2.25 1.95 2.60
2.15 2.18 2.45
2.70 2.60 2.70
3.35 2.90 2.90
4.80 3.60 3.35
9.00 5.30 4.35
140.98 0.631
```

TABLE 8.3

STRUCTURE OF TEMPFILE

0.	522.
38.	522.
53.	522.8
68.	523.8
83.	524.8
99.	526.
114.	527.
129.	528.3
144.	529.3
160.	530.5
175.	531.8
190.	533.0
205.	534.5
217.	535.8
236.	537.8
251.	539.3
266.	540.8
281.	542.3
297.	543.8
312.	545.3
327.	546.8
342.	548.5
358.	550.3
373.	552.3
388.	553.8
407.	556.
419.	557.
434.	558.3
449.	559.5
464.	561.
480.	562.3
495.	563.5
510.	564.5
525.	565.5
541.	566.5
556.	567.0
624.	567.0

TABLE 8.4

STRUCTURE OF FNSYNTH

1	0.1923077	0.1666667	0.2500000	0.0000000E+00	0.1250000
2	0.5000000	0.3888889	0.2500000	0.5000000	0.5625000
3	0.3076923	0.4444444	0.5000000	0.5000000	0.3125000
4	83.37924	17.45821	200.0163	24.08375	
5	1.098084	0.9422973	5.684402	0.9643617	

TABLE 8.5

STRUCTURE OF FNEAST

'P3G07'	0.01	-0.02
'P3G09'	1.3	-0.08
'P3J07'	0.04	-0.10
'P3J09'	-0.03	-0.7
'P3J11'	-0.06	0.05
'P3K10'	0.01	0.02
'P3L09'	-0.15	1.62
'P3M12'	1.23	2.17
'P3P21'	0.	-0.28
'P3Q16'	0.9	-0.05
'P3Q14'	-0.02	-0.49

TABLE 8.6 STRUCTURE OF FNPICKUP

```
'P3J09' 11.95 6
292.    541.4       2.2
392.    551.        2.05
434.    553.8       2.45
438.    554.2       2.45
492.7   558.2       1.75
503.    564.2       2.5
'P3P13' 13.01 6
196.    531.9       4.55
231.    535.2       1.7
347.    545.7       2.5
499.    559.3       6.65
551.    562.6       9.15
582.    563.7       11.5
'P3L09' 14.93 12
185.    531.8       10.5
285.    541.3   9.5
350.    547.7       2.75
410.    553.2       4.
435.    555.5       6.
460.    557.7       13.3
500.    561.3       24.5
513.    562.4       25.75
531.    563.5       34.
547.    564.5       38.
550.    564.6       42.5
580.    566.        55.2
'P3S12' 15.52 4
150.  527.4         2.4
400.  549.7         2.7
500.  557.6         4.55
580.  561.7         7.95
'P3Q14' 15.52 4
150.   527.9        3.2
400.   550.9        3.1
500.   559.3        3.7
580.   563.7        5.7
'P3P13' 15.52 4
150.   528.2        1.7
400.   551.2        2.45
500.   559.8        2.45
580.   564.3        3.2
'P3M12' 15.52 4
150.   528.3        1.55
400.   551.4        1.85
500.   559.7        3.45
580.   564.4        3.25
'P3K10' 15.52 4
150.   528.5        2.25
400.   552.5        2.45
500.   561.3        2.55
580.   566.         2.85
'P3J11' 15.52 4
150.   528.3        2.25
400.   551.         1.75
500.   559.6        2.3
580.   564.1        3.0
```

APPENDIX 9

Output Files

The following pages are an example of the output file for a particular run of RABIT_PL for the Pickering Unit 4 reactor.

STUDY OF REACTOR PICKERING 4

SCENARIO

CONTACT RADIUS 2.50000
H VALUE CONTACT 0.01000
H VALUE GAS 0.00600

THE SIMULATION IS TOTALLY RANDOMIZED

GENERAL

REACTOR ZONE IS CENTRAL
NUMBER OF TUBES = 184
NUMBER OF REALIZATIONS IS 10000
THE TEMPERATURE DATAFILE IS TEMPA

THE DISTRIBUTION OF THE TEMPERATURE IS NORMAL
ITS STANDARD DEVIATION IS 0.0000 DEGREES

GARTERSPRINGS

FILENAME FOR SYNTHETIC DISTRIBUTION GS_P4_SYN

THE DISTRIBUTION OF THE CONTACT TIME IS NORMAL
ITS STANDARD DEVIATION IS 0.2500 TIMES THE MEAN

HYDROGEN

THE CHOICE OF DISTRIBUTION IS WEIBULL
THE MEAN IS 6.60 THE SCALE VALUE IS 7.45
THE ST. DEV. IS 3.00 THE SHAPE VALUE IS 2.34
THE CUT-OFF IS 0.00

PICKUP RATES

INFORMATION ON THE PRIMARY PICKUP RATE
****
THE CHOICE OF DISTRIBUTION IS NORMAL
THE MEAN IS 0.40
THE ST. DEV. IS 0.17
THE TEMPERATURE DEPENDENCE IS ARRHENIUS
THE PARAMETERS ARE REF TEMP IS 567.000
BTEMP IS 5340.000
CUT OFF TEMP IS 0.000
THIS VARIABLE IS NOT DEPENDENT ON IRON

INFORMATION ON THE TRANSITION TIME
****
THE CHOICE OF DISTRIBUTION IS NORMAL
THE MEAN IS 13.00
THE ST. DEV. IS 0.13
THE TEMPERATURE DEPENDENCE IS ARRHENIUS
THE PARAMETERS ARE REF TEMP IS 567.000
BTEMP IS 0.000
CUT OFF TEMP IS 0.000
THIS VARIABLE IS NOT DEPENDENT ON IRON
THE TRANSITION TIME IS NOT DEPENDENT ON PU1

INFORMATION ON THE SECONDARY PICKUP RATE
****
THE CHOICE OF DISTRIBUTION IS WEIBULL
THE MEAN IS 1.01 THE SCALE VALUE IS 1.09
THE ST. DEV. IS 0.78 THE SHAPE VALUE IS 1.31
THE CUT-OFF IS 0.00
THE TEMPERATURE DEPENDENCE IS PIECEWISE LINEAR
THE PARAMETERS ARE REF TEMP IS 555.200
BTEMP IS 0.138
CUT OFF TEMP IS 555.200
THIS VARIABLE IS NOT DEPENDENT ON IRON
PU2 IS NOT CORRELATED WITH PU1

THRESHOLD

THE PARAMETERS OF THE THRESHOLD FOR BLISTER FORMATION

H VALUE IS 28000.00000
QSTAR IS 20900.00000
CTP VALUE IS 41000.00000

INFORMATION ON THRESHOLDS FOR CRITICAL BLISTERS

PICK-UP RATES		TEMPERATURE 520.20	543.20	568.20
0.000	MEAN	25.10	30.70	37.70
	S.D.	1.30	1.50	1.90
0.799	MEAN	33.50	37.10	42.50
	S.D.	2.25	1.95	2.60
3.993	MEAN	38.80	40.50	44.50
	S.D.	2.15	2.18	2.45
7.985	MEAN	46.70	46.40	48.80
	S.D.	2.70	2.60	2.70
11.978	MEAN	53.30	51.10	52.30
	S.D.	3.35	2 90	2.90
19.963	MEAN	65.00	59.20	58.30
	S.D.	4.80	3.60	3.35
39.927	MEAN	92.80	75.50	70.10
	S.D.	9.00	5.30	4.35

TEMPERATURE

RELATIONSHIP BETWEEN CONTACT TEMPERATURE AND PHT TEMPERATURE
THE INTERCEPT IS 140.98000
THE SLOPE IS 0.63100

STATISTICS

INFORMATION ON MONTE CARLO SIMULATIONS FOR EIGHT INPUTS
NUMBER OF REALIZATIONS IS 10000

VARIABLE NAME	MEAN	STANDARD DEVIATION	SKEWNESS
INLET GARTERSPRING	-8.25055	21.42489	-1.72663
OUTLET GARTERSPRING	2.71691	30.02938	3.16408
TIME TO CONTACT	24.30075	11.53421	0.15509
INITIAL HYDROGEN	6.59842	3.00736	0.40702
HYDROGEN THRESHOLD	40.41238	3.49690	0.32978
PRIMARY PICK-UP	0.32596	0.14177	0.42821
SECONDARY PICK-UP	2.64875	1.13808	2.07556
TRANSITION TIME	12.99969	0.13172	1.19113

PROBABILITY OF BLISTERS: EAST INLETS

SCALE=100

X	Y *	Y1 +	0	20	40	60	80	100
1.0	.00E+00	.00E+00	+					
2.0	.00E+00	.00E+00	+					
3.0	.00E+00	.00E+00	+					
4.0	.00E+00	.00E+00	+					
5.0	.00E+00	.00E+00	+					
6.0	.00E+00	.00E+00	+					
7.0	.00E+00	.00E+00	+					
8.0	.00E+00	.00E+00	+					
9.0	.00E+00	.00E+00	+					
10.0	.00E+00	.00E+00	+					
11.0	.00E+00	.00E+00	+					
12.0	.00E+00	.00E+00	+					
13.0	.00E+00	.00E+00	+					
14.0	.60E-03	.00E+00	+					
15.0	.40E-02	.00E+00	+					
16.0	.14E-01	.00E+00	+ *					
17.0	.32E-01	.40E-03	+ *					
18.0	.54E-01	.80E-03	+ *					
19.0	.77E-01	.28E-02	+ *					
20.0	.10E+00	.84E-02	+ *					
21.0	.13E+00	.16E-01	+ *					
22.0	.16E+00	.27E-01	+ *					
23.0	.19E+00	.38E-01	+ *					
24.0	.23E+00	.53E-01	+ *					
25.0	.26E+00	.69E-01	+ *					
26.0	.30E+00	.86E-01	+ *					
27.0	.34E+00	.11E+00	+ *					
28.0	.38E+00	.13E+00	+ *					
29.0	.42E+00	.16E+00	+ *					
30.0	.45E+00	.19E+00	+ *					

PROBABILITY OF BLISTERS: WEST INLETS

SCALE=100

X	Y *	Y1 +	0	20	40	60	80	100
1.0	.00E+00	.00E+00	+					
2.0	.00E+00	.00E+00	+					
3.0	.00E+00	.00E+00	+					
4.0	.00E+00	.00E+00	+					
5.0	.00E+00	.00E+00	+					
6.0	.00E+00	.00E+00	+					
7.0	.00E+00	.00E+00	+					
8.0	.00E+00	.00E+00	+					
9.0	.00E+00	.00E+00	+					
10.0	.00E+00	.00E+00	+					
11.0	.00E+00	.00E+00	+					
12.0	.00E+00	.00E+00	+					
13.0	.00E+00	.00E+00	+					
14.0	.20E-03	.00E+00	+					
15.0	.22E-02	.00E+00	+					
16.0	.88E-02	.00E+00	+*					
17.0	.20E-01	.00E+00	+ *					
18.0	.42E-01	.10E-02	+ *					
19.0	.66E-01	.32E-02	+ *					
20.0	.92E-01	.68E-02	+ *					
21.0	.13E+00	.14E-01	+ *					
22.0	.16E+00	.24E-01	+ *					
23.0	.19E+00	.34E-01	+ *					
24.0	.23E+00	.48E-01	+ *					
25.0	.26E+00	.62E-01	+ *					
26.0	.30E+00	.80E-01	+ *					
27.0	.34E+00	.10E+00	+ *					
28.0	.38E+00	.13E+00	+ *					
29.0	.42E+00	.15E+00	+ *					
30.0	.46E+00	.18E+00	+ *					

GENERAL

REACTOR ZONE IS INTERMEDIATE
NUMBER OF TUBES = 156
NUMBER OF REALIZATIONS IS 10000
THE TEMPERATURE DATAFILE IS TEMPA

THE DISTRIBUTION OF THE TEMPERATURE IS NORMAL
ITS STANDARD DEVIATION IS 0.0000 DEGREES

GARTERSPRINGS

FILENAME FOR SYNTHETIC DISTRIBUTION GS_P4_SYN

THE DISTRIBUTION OF THE CONTACT TIME IS NORMAL
ITS STANDARD DEVIATION IS 0.2500 TIMES THE MEAN

HYDROGEN

THE CHOICE OF DISTRIBUTION IS WEIBULL
THE MEAN IS 6.65 THE SCALE VALUE IS 7.50
THE ST. DEV. IS 2.90 THE SHAPE VALUE IS 2.45
THE CUT-OFF IS 0.00

PICKUP RATES

INFORMATION ON THE PRIMARY PICKUP RATE
****
THE CHOICE OF DISTRIBUTION IS NORMAL
THE MEAN IS 0.40
THE ST. DEV. IS 0.17
THE TEMPERATURE DEPENDENCE IS ARRHENIUS
THE PARAMETERS ARE REF TEMP IS 567.000
BTEMP IS 5340.000
CUT OFF TEMP IS 0.000
THIS VARIABLE IS NOT DEPENDENT ON IRON

INFORMATION ON THE TRANSITION TIME
****
THE CHOICE OF DISTRIBUTION IS NORMAL
THE MEAN IS 13.00
THE ST. DEV. IS 0.13
THE TEMPERATURE DEPENDENCE IS ARRHENIUS
THE PARAMETERS ARE REF TEMP IS 567.000
BTEMP IS 0.000
CUT OFF TEMP IS 0.000
THIS VARIABLE IS NOT DEPENDENT ON IRON
THE TRANSITION TIME IS NOT DEPENDENT ON PU1

INFORMATION ON THE SECONDARY PICKUP RATE
****
THE CHOICE OF DISTRIBUTION IS WEIBULL
THE MEAN IS 1.01 THE SCALE VALUE IS 1.09
THE ST. DEV. IS 0.78 THE SHAPE VALUE IS 1.31
THE CUT-OFF IS 0.00
THE TEMPERATURE DEPENDENCE IS PIECEWISE LINEAR
THE PARAMETERS ARE REF TEMP IS 555.200
BTEMP IS 0.138
CUT OFF TEMP IS 555.200
THIS VARIABLE IS NOT DEPENDENT ON IRON
PU2 IS NOT CORRELATED WITH PU1

THRESHOLD

THE PARAMETERS OF THE THRESHOLD FOR BLISTER FORMATION

H VALUE IS 28000.00000
QSTAR IS 20900.00000
CTP VALUE IS 41000.00000

INFORMATION ON THRESHOLDS FOR CRITICAL BLISTERS

PICK-UP RATES		TEMPERATURE 520.20	543.20	568.20
0.000	MEAN	25.10	30.70	37.70
	S.D.	1.30	1.50	1.90
0.799	MEAN	33.50	37.10	42.50
	S.D.	2.25	1.95	2.60
3.993	MEAN	38.80	40.50	44.50
	S.D.	2.15	2.18	2.45
7.985	MEAN	46.70	46.40	48.80
	S.D.	2.70	2.60	2.70
11.978	MEAN	53.30	51.10	52.30
	S.D.	3.35	2.90	2.90
19.963	MEAN	65.00	59.20	58.30
	S.D.	4.80	3.60	3.35
39.927	MEAN	92.80	75.50	70.10
	S.D.	9.00	5.30	4.35

TEMPERATURE

RELATIONSHIP BETWEEN CONTACT TEMPERATURE AND PHT TEMPERATURE
THE INTERCEPT IS 140.98000
THE SLOPE IS 0.63100

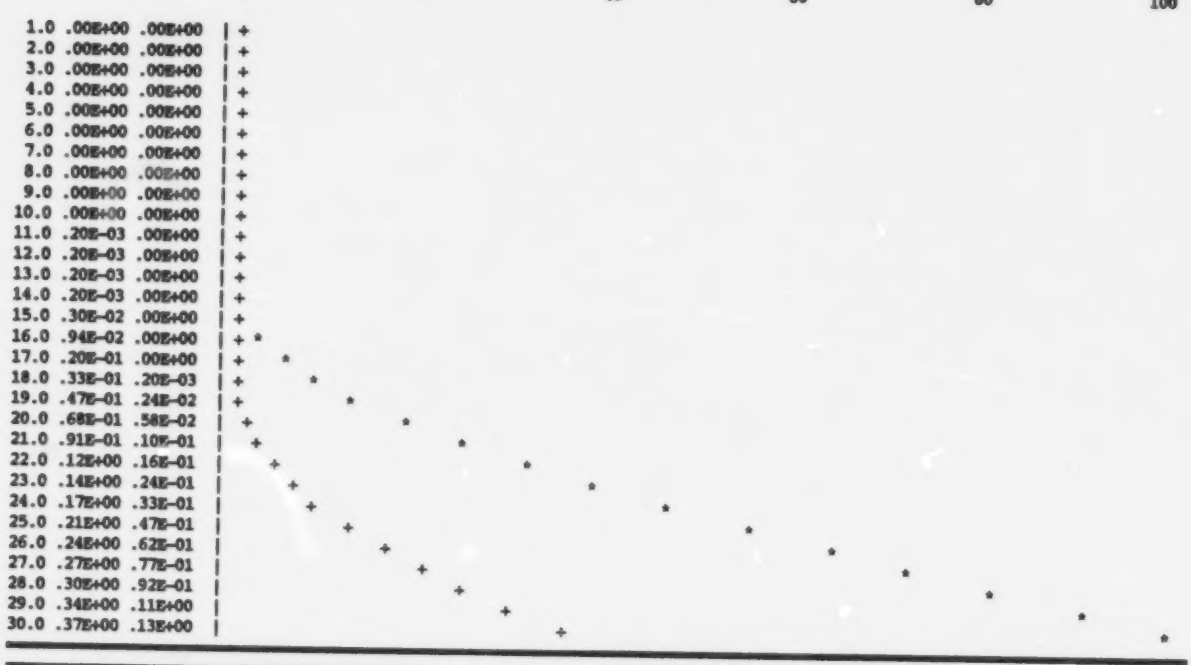
STATISTICS

INFORMATION ON MONTE CARLO SIMULATIONS FOR EIGHT INPUTS
NUMBER OF REALIZATIONS IS 10000

VARIABLE NAME	MEAN	STANDARD DEVIATION	SKEWNESS
INLET GARTERSPRING	-7.61073	21.05395	-1.68521
OUTLET GARTERSPRING	2.61596	30.04637	3.33445
TIME TO CONTACT	28.34932	14.04674	0.49616
INITIAL HYDROGEN	6.64293	2.93470	0.38959
HYDROGEN THRESHOLD	39.96727	3.22405	0.31308
PRIMARY PICK-UP	0.31865	0.13478	0.38576
SECONDARY PICK-UP	2.53700	1.01882	1.78511
TRANSITION TIME	13.00018	0.12733	1.05050

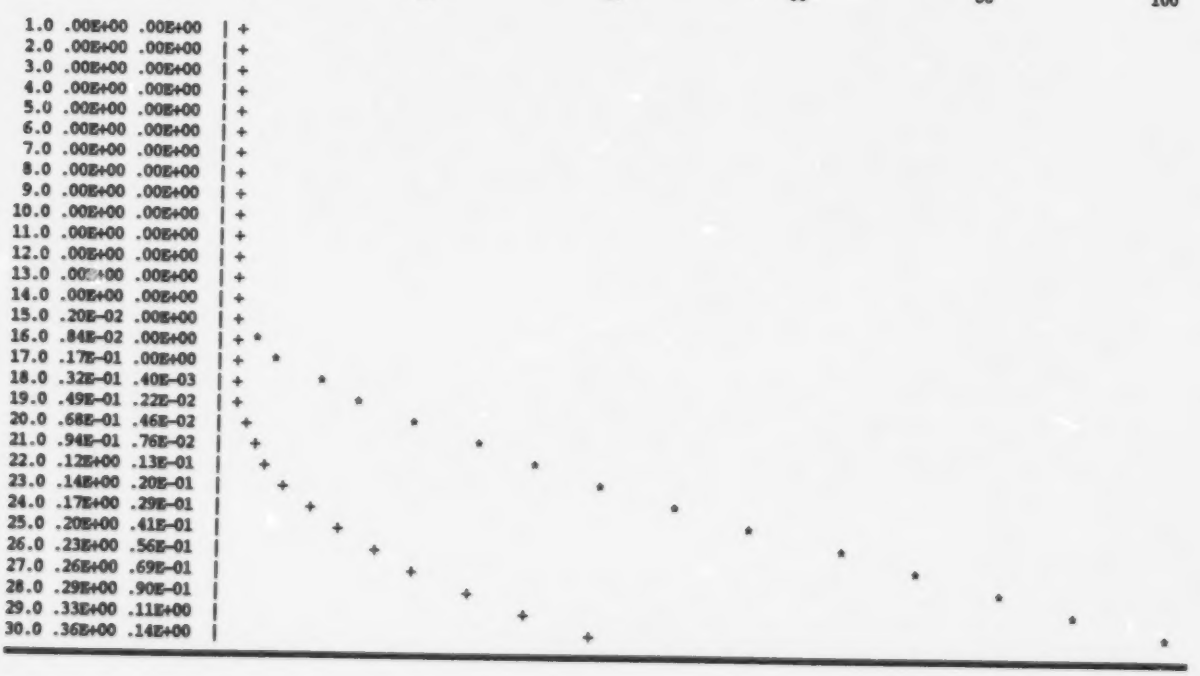
PROBABILITY OF BLISTERS: EAST INLETS

X	Y *	Y1 +
1.0	.00E+00	.00E+00
2.0	.00E+00	.00E+00
3.0	.00E+00	.00E+00
4.0	.00E+00	.00E+00
5.0	.00E+00	.00E+00
6.0	.00E+00	.00E+00
7.0	.00E+00	.00E+00
8.0	.00E+00	.00E+00
9.0	.00E+00	.00E+00
10.0	.00E+00	.00E+00
11.0	.20E-03	.00E+00
12.0	.20E-03	.00E+00
13.0	.20E-03	.00E+00
14.0	.20E-03	.00E+00
15.0	.30E-02	.00E+00
16.0	.94E-02	.00E+00
17.0	.20E-01	.00E+00
18.0	.33E-01	.20E-03
19.0	.47E-01	.24E-02
20.0	.68E-01	.58E-02
21.0	.91E-01	.10E-01
22.0	.12E+00	.16E-01
23.0	.14E+00	.24E-01
24.0	.17E+00	.33E-01
25.0	.21E+00	.47E-01
26.0	.24E+00	.62E-01
27.0	.27E+00	.77E-01
28.0	.30E+00	.92E-01
29.0	.34E+00	.11E+00
30.0	.37E+00	.13E+00



PROBABILITY OF BLISTERS: WEST INLETS

X	Y *	Y1 +
1.0	.00E+00	.00E+00
2.0	.00E+00	.00E+00
3.0	.00E+00	.00E+00
4.0	.00E+00	.00E+00
5.0	.00E+00	.00E+00
6.0	.00E+00	.00E+00
7.0	.00E+00	.00E+00
8.0	.00E+00	.00E+00
9.0	.00E+00	.00E+00
10.0	.00E+00	.00E+00
11.0	.00E+00	.00E+00
12.0	.00E+00	.00E+00
13.0	.00E+00	.00E+00
14.0	.00E+00	.00E+00
15.0	.20E-02	.00E+00
16.0	.84E-02	.00E+00
17.0	.17E-01	.00E+00
18.0	.32E-01	.40E-03
19.0	.49E-01	.22E-02
20.0	.68E-01	.46E-02
21.0	.94E-01	.76E-02
22.0	.12E+00	.13E-01
23.0	.14E+00	.20E-01
24.0	.17E+00	.29E-01
25.0	.20E+00	.41E-01
26.0	.23E+00	.56E-01
27.0	.26E+00	.69E-01
28.0	.29E+00	.90E-01
29.0	.33E+00	.11E+00
30.0	.36E+00	.14E+00



GENERAL

REACTOR ZONE IS OUTER
NUMBER OF TUBES = 50
NUMBER OF REALIZATIONS IS 10000
THE TEMPERATURE DATAFILE IS TEMPA

THE DISTRIBUTION OF THE TEMPERATURE IS NORMAL
ITS STANDARD DEVIATION IS 0.0000 DEGREES

GARTENSPRINGS

FILENAME FOR SYNTHETIC DISTRIBUTION GS_P4_SYN

THE DISTRIBUTION OF THE CONTACT TIME IS NORMAL
ITS STANDARD DEVIATION IS 0.2500 TIMES THE MEAN

HYDROGEN

THE CHOICE OF DISTRIBUTION IS WEIBULL
THE MEAN IS 6.85 THE SCALE VALUE IS 7.70
THE ST. DEV. IS 2.75 THE SHAPE VALUE IS 2.68
THE CUT-OFF IS 0.00

PICKUP RATES

INFORMATION ON THE PRIMARY PICKUP RATE
****
THE CHOICE OF DISTRIBUTION IS NORMAL
THE MEAN IS 0.40
THE ST. DEV. IS 0.17
THE TEMPERATURE DEPENDENCE IS ARRHENIUS
THE PARAMETERS ARE REF TEMP IS 567.000
BTEMP IS 5340.000
CUT OFF TEMP IS 0.000
THIS VARIABLE IS NOT DEPENDENT ON IRON

INFORMATION ON THE TRANSITION TIME
****
THE CHOICE OF DISTRIBUTION IS NORMAL
THE MEAN IS 13.00
THE ST. DEV. IS 0.13
THE TEMPERATURE DEPENDENCE IS ARRHENIUS
THE PARAMETERS ARE REF TEMP IS 567.000
BTEMP IS 0.000
CUT OFF TEMP IS 0.000
THIS VARIABLE IS NOT DEPENDENT ON IRON
THE TRANSITION TIME IS NOT DEPENDENT ON PU1

INFORMATION ON THE SECONDARY PICKUP RATE
****
THE CHOICE OF DISTRIBUTION IS WEIBULL
THE MEAN IS 1.01 THE SCALE VALUE IS 1.09
THE ST. DEV. IS 0.78 THE SHAPE VALUE IS 1.31
THE CUT-OFF IS 0.00
THE TEMPERATURE DEPENDENCE IS PIECEWISE LINEAR
THE PARAMETERS ARE REF TEMP IS 555.200
BTEMP IS 0.138
CUT OFF TEMP IS 555.200
THIS VARIABLE IS NOT DEPENDENT ON IRON
PU2 IS NOT CORRELATED WITH PU1

THRESHOLD

THE PARAMETERS OF THE THRESHOLD FOR BLISTER FORMATION

H VALUE IS 28000.00000
QSTAR IS 20900.00000
CTP VALUE IS 41000.00000

INFORMATION ON THRESHOLDS FOR CRITICAL BLISTERS

PICK-UP RATES		TEMPERATURE 520.20	543.20	568.20
0.000	MEAN	25.10	30.70	37.70
	S.D.	1.30	1.50	1.90
0.799	MEAN	33.50	37.10	42.50
	S.D.	2.25	1.95	2.60
3.993	MEAN	38.80	40.50	44.50
	S.D.	2.15	2.18	2.45
7.985	MEAN	46.70	46.40	48.80
	S.D.	2.70	2.60	2.70
11.978	MEAN	53.30	51.10	52.30
	S.D.	3.35	2.90	2.90
19.963	MEAN	65.00	59.20	58.30
	S.D.	4.80	3.60	3.35
39.927	MEAN	92.80	75.50	70.10
	S.D.	9.00	5.30	4.35

TEMPERATURE

RELATIONSHIP BETWEEN CONTACT TEMPERATURE AND PHT TEMPERATURE
THE INTERCEPT IS 140.98000
THE SLOPE IS 0.63100

STATISTICS

INFORMATION ON MONTE CARLO SIMULATIONS FOR EIGHT INPUTS
NUMBER OF REALIZATIONS IS 10000

VARIABLE NAME	MEAN	STANDARD DEVIATION	SKEWNESS
INLET GARTERSPRING	-8.18375	21.20987	-1.89446
OUTLET GARTERSPRING	2.85586	29.50524	3.21526
TIME TO CONTACT	46.95550	24.34047	0.54888
INITIAL HYDROGEN	6.87010	2.78102	0.28143
HYDROGEN THRESHOLD	40.08096	3.24813	0.25976
PRIMARY PICK-UP	0.31632	0.13868	0.71161
SECONDARY PICK-UP	2.56468	0.96482	1.83321
TRANSITION TIME	12.99613	0.13006	-3.04952

PROBABILITY OF BLISTERS: EAST INLETS

X	Y *	Y1 +	0 SCALE=100 20 40 60 80 100
1.0	.00E+00	.00E+00	+
2.0	.00E+00	.00E+00	+
3.0	.00E+00	.00E+00	+
4.0	.00E+00	.00E+00	+
5.0	.00E+00	.00E+00	+
6.0	.00E+00	.00E+00	+
7.0	.00E+00	.00E+00	+
8.0	.00E+00	.00E+00	+
9.0	.00E+00	.00E+00	+
10.0	.00E+00	.00E+00	+
11.0	.00E+00	.00E+00	+
12.0	.00E+00	.00E+00	+
13.0	.20E-03	.00E+00	+
14.0	.20E-03	.00E+00	+
15.0	.12E-02	.00E+00	+
16.0	.48E-02	.00E+00	+ *
17.0	.12E-01	.00E+00	+ *
18.0	.19E-01	.20E-03	+ *
19.0	.28E-01	.60E-03	+ *
20.0	.37E-01	.12E-02	+ *
21.0	.47E-01	.40E-02	+ *
22.0	.56E-01	.74E-02	+ *
23.0	.67E-01	.12E-01	+ *
24.0	.77E-01	.15E-01	+ *
25.0	.89E-01	.21E-01	+ *
26.0	.10E+00	.28E-01	+ *
27.0	.12E+00	.35E-01	+ *
28.0	.13E+00	.43E-01	+ *
29.0	.14E+00	.49E-01	+ *
30.0	.15E+00	.56E-01	+ *

PROBABILITY OF BLISTERS: WEST INLETS

X	Y *	Y1 +	0 SCALE=100 20 40 60 80 100
1.0	.00E+00	.00E+00	+
2.0	.00E+00	.00E+00	+
3.0	.00E+00	.00E+00	+
4.0	.00E+00	.00E+00	+
5.0	.00E+00	.00E+00	+
6.0	.00E+00	.00E+00	+
7.0	.00E+00	.00E+00	+
8.0	.00E+00	.00E+00	+
9.0	.00E+00	.00E+00	+
10.0	.00E+00	.00E+00	+
11.0	.00E+00	.00E+00	+
12.0	.00E+00	.00E+00	+
13.0	.00E+00	.00E+00	+
14.0	.00E+00	.00E+00	+
15.0	.14E-02	.00E+00	+
16.0	.42E-02	.00E+00	+ *
17.0	.11E-01	.20E-03	+ *
18.0	.21E-01	.40E-03	+ *
19.0	.29E-01	.10E-02	+ *
20.0	.36E-01	.24E-02	+ *
21.0	.47E-01	.46E-02	+ *
22.0	.59E-01	.74E-02	+ *
23.0	.70E-01	.14E-01	+ *
24.0	.82E-01	.19E-01	+ *
25.0	.93E-01	.25E-01	+ *
26.0	.10E+00	.32E-01	+ *
27.0	.12E+00	.37E-01	+ *
28.0	.13E+00	.44E-01	+ *
29.0	.14E+00	.52E-01	+ *
30.0	.16E+00	.60E-01	+ *

RELIABILITY VS. TIME

X	Y	0	20	40	60	80	100
1.000	1.00000	|					*
2.000	1.00000	|					*
3.000	1.00000	|					*
4.000	1.00000	|					*
5.000	1.00000	|					*
6.000	1.00000	|					*
7.000	1.00000	|					*
8.000	1.00000	|					*
9.000	1.00000	|					*
10.000	1.00000	|					*
11.000	1.00000	|					*
12.000	1.00000	|					*
13.000	1.00000	|					*
14.000	1.00000	|					*
15.000	1.00000	|					*
16.000	1.00000	|					*
17.000	0.95905	|					*
18.000	0.79653	|				*	
19.000	0.38594	|		*			
20.000	0.09954	|	*				
21.000	0.01190	| *					
22.000	0.00063	| *					
23.000	0.00002	| *					
24.000	0.00000	| *					
25.000	0.00000	| *					
26.000	0.00000	| *					
27.000	0.00000	| *					
28.000	0.00000	| *					
29.000	0.00000	| *					
30.000	0.00000	| *					

AVERAGE NUMBER BLISTERED TUBES VS TIME

SCALE=100

X	Y *	Y1 +	0 20 40 60 80 100
1.0	.00E+00	.00E+00	+
2.0	.00E+00	.00E+00	+
3.0	.00E+00	.00E+00	+
4.0	.00E+00	.00E+00	+
5.0	.00E+00	.00E+00	+
6.0	.00E+00	.00E+00	+
7.0	.00E+00	.00E+00	+
8.0	.00E+00	.00E+00	+
9.0	.00E+00	.00E+00	+
10.0	.00E+00	.00E+00	+
11.0	.16E-01	.00E+00	+
12.0	.16E-01	.00E+00	+
13.0	.21E-01	.00E+00	+
14.0	.94E-01	.00E+00	+
15.0	.10E+01	.00E+00	+
16.0	.37E+01	.00E+00	+ *
17.0	.83E+01	.42E-01	+ *
18.0	.15E+02	.23E+00	+ *
19.0	.22E+02	.95E+00	+ *
20.0	.30E+02	.23E+01	+ *
21.0	.40E+02	.44E+01	+ *
22.0	.51E+02	.73E+01	+ *
23.0	.61E+02	.11E+02	+ *
24.0	.72E+02	.15E+02	+ *
25.0	.85E+02	.20E+02	+ *
26.0	.97E+02	.26E+02	+ *
27.0	.11E+03	.32E+02	+ *
28.0	.12E+03	.40E+02	+ *
29.0	.14E+03	.49E+02	+ *
30.0	.15E+03	.57E+02	+ *

STANDARD DEVIATION VS TIME

SCALE=100

X	Y *	Y1 +	0 20 40 60 80 100
1.0	.00E+00	.00E+00	+
2.0	.00E+00	.00E+00	+
3.0	.00E+00	.00E+00	+
4.0	.00E+00	.00E+00	+
5.0	.00E+00	.00E+00	+
6.0	.00E+00	.00E+00	+
7.0	.00E+00	.00E+00	+
8.0	.00E+00	.00E+00	+
9.0	.00E+00	.00E+00	+
10.0	.00E+00	.00E+00	+
11.0	.13E+00	.00E+00	+*
12.0	.13E+00	.00E+00	+*
13.0	.14E+00	.00E+00	+*
14.0	.31E+00	.00E+00	+ *
15.0	.10E+01	.00E+00	+ *
16.0	.19E+01	.00E+00	+ *
17.0	.29E+01	.21E+00	+ *
18.0	.38E+01	.48E+00	+ *
19.0	.46E+01	.98E+00	+ *
20.0	.53E+01	.15E+01	+ *
21.0	.60E+01	.21E+01	+ *
22.0	.67E+01	.27E+01	+ *
23.0	.72E+01	.32E+01	+ *
24.0	.77E+01	.38E+01	+ *
25.0	.81E+01	.44E+01	+ *
26.0	.85E+01	.49E+01	+ *
27.0	.88E+01	.55E+01	+ *
28.0	.91E+01	.60E+01	+ *
29.0	.93E+01	.65E+01	+ *
30.0	.95E+01	.70E+01	+ *